PROCEEDINGS

CONFERENCE ON FIRE & FOREST METEOROLOGY

10th
10ième

Ottawa, Canada

CONGRES SUR LES INCENDIES ET LA METEOROLOGIE FORESTIERE

COMPTE RENDU

PROCEEDINGS OF THE 10th CONFERENCE ON FIRE AND FOREST METEOROLOGY

COMPTE RENDU DU 10ième CONGRES SUR LES INCENDIES ET LA METEOROLOGIE FORESTIERE

1989

EDITORS / EDITEURS

D. C. MACIVER, H. AULD,
R. WHITEWOOD

93-02188/

EDITORIAL REVIEW BOARD

H. E. AULD	ENVIRONMENT CANADA
D. E. DUBE	FORESTRY CANADA
M. FLANNIGAN	FORESTRY CANADA
D. C. MACIVER	ENVIRONMENT CANADA
D. J. MCRAE	FORESTRY CANADA
L. POULIOT	ENVIRONMENT CANADA
R. B. STREET	ENVIRONMENT CANADA
P. C. WARD	ONTARIO MINISTRY OF NATURAL RESOURCES
R. WHITEWOOD	ENVIRONMENT CANADA
P. M. WOODARD	UNIVERSITY OF ALBERTA

All manuscripts were subject to editorial review plus author and editorial approval prior to publication.

For additional information or copies of the Proceedings, contact:

M. Flannigan
Forestry Canada
Petawawa National Forestry Institute
P.O. Box 2000
Chalk River, Ontario
K0J 1J0

P. Woodard
Department of Forest Science
855 General Services Building
University of Alberta
Edmonton, Alberta
T6G 2H1

D.C. MacIver or H. Auld
Canadian Climate Centre
Atmospheric Environment Service
4905 Dufferin Street
Downsview, Ontario
M3H 5T4

PUBLICATION DATA:

Title: Proceedings of the 10th Conference on Fire and Forest Meteorology

Includes papers and abstracts in French

Grateful acknowledgement is extended to Forestry Canada and Environment Canada for additional support in the preparation of the proceedings.

Table of Contents

Foreword 13

Welcoming Remarks

Mr. Howard Ferguson, Assistant Deputy Minister
- Atmospheric Environment Service, Environment Canada 15
Mr. Jean Claude Mercier, Deputy Minister, Forestry Canada 19
Mr. Bob Burgar, Assistant Deputy Minister for Southern Ontario
- Ontario Ministry of Natural Resources 23
Mr. Regis Proulx on behalf of Dr. Gilbert Paillé, Deputy Minister
- Quebec Ministère de l'Energie et des Ressources 25

SESSION 1: LIGHTNING & FOREST METEOROLOGY
Moderator: Bob Dickison, University of New Brunswick
Fredericton, NB.

KEYNOTE: Artificial Intelligence; Where Are We? Whither?
D. Latham 27

KEYNOTE: Lightning Detection Systems: A Status Report.
H. Newhouse 28

Ground Truthing of LLP Lightning Location Data in Alberta.
N. Nimchuk 33

Spatially Integrated Radiation Under Lodgepole Pine Canopies.
D.F. Potts and R. Hungerford 41

Aerodynamic Parameters of a Mature Mixed Forest.
D. Branson 44

Use of Minisonde Observations for On-site Fire Behaviour
Prediction. B. Burke and P.C. Ward 54

An Evaluation of a 3-D Diagnostic Wind Flow Model (NUATMOS)
with Implications for Its Use.
B.H. Connell, G.L. Woolridge and D.G. Fox 58

An Extensive Blowdown Occurrence in Northwestern Ontario.
M.D. Flannigan, T.J. Lynham and P.C. Ward 65

The California Lightning Fires of 1987.
F.M. Fujioka and N.A. Dean 72

Burning Out in Mountainous Terrain: Some Meteorological and Forest
Fuel Considerations. R.A. Lanoville and W.M. Mawdsley 78

LUNCHEON

KEYNOTE: New Technologies: A Total System Perspective.
S. Gordon 84

SESSION 2: PRESCRIBED BURNING AND FIRE EFFECTS
Moderator: Brad Hawkes, Forestry Canada, Pacific Forestry Centre, Victoria, BC.

KEYNOTE: The Future of Prescribed Fire: Concern and Knowledge Needs. J.K. Brown 89

KEYNOTE: Prescribed Burning in Canada: Progress and Problems. P.C. Ward 97

Fire Acceleration Rates on Large-Scale Convection Burns. D.J. McRae, B.J. Stocks and C.J. Ogilvie 101

Cambium Mortality Resulting From Broadcast Burning in Mixed Conifer Shelterwoods. K.C. Ryan and B.M. Steele 108

Prescribed Fire - A Cost Effective Control for White Pine Cone Beetle. D. Wade, G. Debarr, L.R. Barber and E. Manchester 117

Factors Affecting White Spruce (Picea glauca [Moench] Voss) Seed Germination On Burned Forest Litter. M.R. Coyea, V.J. Lieffers and P.M. Woodard 122

Estimation of Nutrient Loss to the Atmosphere From Slashburns in British Columbia. M.C. Feller 126

Institutional Constraints Affect Prescribed Burning Costs Variability: Preliminary Findings A. Gonzàlez-Cabàn and L.F. Bednar 136

Soil Nutrient and Pinyon Seeding Response to Fire Severity. M.G. Harrington 143

Modeling the Downward Heat Pulse From Fire in Soils and in Plant Tissue. R.D. Hungerford 148

Fuels Consumption From Prescribed Fire in Northern Idaho Logging Slash. E.D. Reinhardt, J.K. Brown and W.C. Fischer 155

Survival and Growth Effects of Young Southern Pines After Simulated Crown Scorch. D.R. Weiss, D.D. Wade and R.W. Johansen 161

SESSION 3: CLIMATE CHANGE
Moderator: John Powell, Forestry Canada, Northern Forestry Centre, Edmonton, Alta.

KEYNOTE: Climate Change and Wildfire in Northern Coniferous Forests: Climate Change Scenarios. R. Wein 169

Climate Change Update. J.B. Harrington 170

Changing Climatic Resources for the Western Canada Boreal Forest E. Wheaton and J.P. Thorpe 171

Climate Change and Forest Fires in Ontario. R.B. Street 177

SESSION 4: SMOKE MANAGEMENT AND AIR QUALITY
Moderator: B. Stocks, Forestry Canada,
Great Lakes Forestry Centre, Sault Ste. Marie, Ontario

KEYNOTE: Smoke Management and Air Quality. W.T. Sommers 183

Air Toxics and Fireline Exposure. D.E. Ward 184

Automatic Smoke Management System (ASMS). R. Gilbert 194

SESSION 5: FOREST HEALTH AND PRODUCTIVITY
Moderator: Paul Addison, Forestry Canada, Forest Science Directorate,
Ottawa, Ont.

KEYNOTE: Protecting the Health and Productivity of the Boreal Estate. D.C. MacIver 195

Yield Forecasts for Aspen Stands
J.P. Carpentier 200

SESSION 6: FIRE BEHAVIOR/DANGER
Moderator: Pat Andrews, USDA Forest Service, Intermountain
Fire Sciences Lab., Missoula, MT.

KEYNOTE: Prediction of Crown Fire Behaviour in Conifer Stands.
C.E. Van Wagner 207

A Weather-Based Fire Season Model.
A.J. Simard, J.E. Eenigenburg and W.A. Main 213

A Markov Chain Model of a Forest Fire Danger Rating Index.
D.L. Martell 225

Suitability of the Canadian Forest Fire Danger Rating System
for Use in the Daxinganling Forestry Management Bureau,
Heilongjaing Province, China. T.J. Lynham and B.J. Stocks 232

Field Evaluation of a Moisture Content Model for Medium-Sized Logging Slash. B.D. Lawson, and B.C. Hawkes 247

The Influence of Fuel Packing, Moisture and Inorganic Contents on the Heat Evolved From Smoldering Peat. W.H. Frandsen 258

Fire Behavior and Effects in Aspen-Northern Hardwoods Stands.
M.E. Alexander and R.W. Sando 263

1978 National Fire Danger Rating Systems Revisions
R.E. Burgan 275

Smoldering Combustion Limits in Peat as Influenced by Moisture, Mineral Content, and Organic Bulk Density. R.A. Hartford 282

Predicted vs. Observed Fire Spread Rates in Ponderosa Pine Fuel Beds: A Test of American and Canadian Systems.
R.S. McAlpine and G. Xanthopoulos 287

Modelling Diurnal Fire Fuel Moisture Behavoir.
D.F. Potts and G.A. Morris 295

Water Dynamics of Peat Due to Subsurface Recharge.
P.G. Rivard and P.M. Woodard 298

SESSION 7: FIRE MANAGEMENT
Moderator: Bob Bailey, Territorial Forest Fire Centre, Dept. of
Renewable Resources, Fort Smith, NWT.

KEYNOTE: Management Information for Fire Protection. R. Proulx 303

Application of a PC-Based Fire Management Information System in
New Brunswick. W.G. Clowater, I.R. Methven, and U. Feunekes 308

Integrating Geographic Information Systems Into Fire Management.
L.A. Salazar, and C.V. Nilsson 311

Application of Fire Growth Simulation Model in Fire Management.
P.L. Andrews 317

Development of an Automated Hourly Fire Weather Network and Its Application
to Fire Management in British Columbia. S.K. Grimaldi, and V.E. Fletcher 322

Forest Fire Protection in Bulgaria, Making Forests less
Combustible. Y. Kurpanov 325

Technology Transfer in Saskatchewan: Operational Use of the Canadian
Forest Fire Danger Rating System. W.J. DeGroot 327

The Effect of Hourly Weather on Fire Areas in the FBP System
U. Feunekes, and I.R. Methven 333

The Québec Forest Protection Management System
J. Guenette 337

GIS Application in Fire Management. R. Van Wyngaarden and T. Grimes 338

The Spatial Analysis Approach for Forest Fire Preparedness Planning.
B.S. Lee and K.R. Anderson 339

Fire Detection Using the NOAA-N Satellites. G. Stephens and M. Matson 346

Monitoring the 1987 Extreme Fires in Daxinanlin and Post-Fire Survey
Using Remote Sensing Images. Yang Yun-qian and Li Quan-bin 351

BANQUET

KEYNOTE: A Historical Perspective of Forestry in Canada.
J.C. Mercier 356

SESSION 8: FIRE WEATHER/CLIMATE
Moderator: Ben Janz, Alberta Forestry Service, Provincial Forest
Fire Centre, Edmonton, Alta.

KEYNOTE: The Climate Background and Weather Conditions of
1987 Daxinanlin Extreme Forest Fire In China.
Yang Yun-qian and Jin Ji-zhong 364

Use of Numerical Weather Prediction Models for Medium/Extended-Range Fire
Weather Forecasting. K. Ueyoshi and J.O. Roads 377

Spatial Interpolation of Fire Potential Forecasts in Complex Terrain of California. M.H. McCutchan and T.H. Tsou 384

Forecasting Wildfire "Blow Up". B.B. Aronovitch 391

Forecasting Method of Precipitation for the Calculation of the Canadian Forest Fire Weather Index System L. Pouliot 400

Seasonal Change in Live Fuel Moisture of Understory Plants in Western U.S. Aspen. J.K. Brown, G.D. Booth and D.G. Simmerman 406

Heat Related Water Transport in Woody Plants: Summary of Experimental Results. W.B. Cohen, P.N. Omi and R.C. Rothermal 413

Analysis of the Fire Behavior Associated with Three 1988 Spring Wild Fires in Central Canada. K.G. Hirsch 416

Specification of Monthly Mean Anomalies of Fire Weather Elements from Concurrent Anomalies of the Mean 700 MB Height Field. W.H. Klein and B.T. Whistler 426

The Relationship Between Mean Monthly Fire Potential Indices and Monthly Fire Severity. M.H. McCutchan and W.A. Main 430

The Application of a Micro-Computer Based System to Fire Weather Support B. J. Snyder 436

Fire Weather Forecast Program. R. Winterer 440

Author's Addresses 446

Field Trip - Hybrid Poplar Technology 453

Commercial Exhibitors' Addresses 454

Photographs 455

Table des Matières

Avant-propos mots de beinvenu 13

Howard Ferguson, sous-ministre adjoint
- Environnement Canada, Service de l'Environnement atmosphérique 15
Jean Claude Mercier, sous-ministre, Forêts Canada 19
Bob Burgar, sous-ministre adjoint chargé du sud du l'Ontario
- Ministère des Richesses naturelles de l'Ontario 23
Regis Proulx (au lieu de Gilbert Paillé), sous-ministre
- Ministère de l'Énergie et des Ressources du Québec 25

SÉANCE 1: LA FOUDRE ET LA MÉTÉOROLOGIE FORESTIÈRE
Régulateur: Bob Dickison, université du Nouveau-Brunswick, Fredericton, N.-B.

EXPOSÉ PRINCIPAL: L'intelligence artificielle: Où en sommes-nous? Vers où? D. Latham 27

EXPOSÉ PRINCIPAL: Un rapport sur l'état actuel des sytèmes de localisation de la foudre. H. Newhouse 28

Vérification au sol des données du système de localisation de la foudre LLP en alberta. N. Nimchuk 33

Rayonnement intégré dans l'espace sous des couverts de pins tordus. D.F. Potts et R. Hungerford 41

Paramètres aérodynamiques d'une forêt mélangée adulte à Chalk River, Ontario. D. Branson 44

Utilisation d'observations par minisonde pour prédire le comportement d'un incendie sur le terrain. B. Burke et P.C. Ward 54

Une évaluation d'un modèle diagnostique en trois dimensions de l'écoulement du vent (NUATMOS) et des incidences de son utilisation. B.H. Connell, G.L. Woolridge et D.G. Fox 58

Le vent abat beaucoup d'arbres dans le nord-ouest de l'Ontario. M.D. Flannigan, T.J. Lynham et P.C. Ward 65

Les feux de foudre de 1987 de la Californie. F.M. Fujioka et N.A. Dean 72

Brûlage à contrevent en terrain montagneux: considérations relatives aux conditions météorologiques et aux combustibles forestiers. R.A. Lanoville et W.M. Mawdsley 78

DÉJEUNER-CAUSERIE

EXPOSÉ PRINCIPAL: Nouvelles technologies: Une perspective du système en totalité S. Gordon 84

SÉANCE 2: LE BRÛLAGE DIRIGÉ ET SES EFFETS

Régulateur: Brad Hawkes, Forêts Canada, Centre forestier du Pacifique, Victoria, C.-B.

EXPOSÉ PRINCIPAL: Le futur du brûlage dirigé: préoccupations et besoins de connaissances. J.K. Brown 89

EXPOSÉ PRINCIPAL: Le brûlage dirigé au Canada: progrès et problèmes. P.C. Ward 97

Taux d'accélération du feu lors de brûlages à grande échelle déclenchés par allumage central. D.J. McRae, B.J. Stocks et C.J. Ogilvie 101

Mortalité du cambium provoquée par le brûlage extensif dans des abris (peuplements principaux) de conifères mélangés. K.C. Ryan et B.M. Steele 108

Le brûlage dirigé Lutte économiquement efficace contre les populations de scolyte des cônes du pin blanc. D. Wade, G. Debarr, L.R. Barber et E. Manchester 117

Facteurs affectant la germination des graines d'épinette blanche (*Picea glavea* [Moench] Voss) dans la litière brûlée. M.R. Coyea, V.J. Lieffers et P.M. Woodard 122

Estimation de la quantité d'éléments nutritifs dissipée dans l'atmosphère par des brûlages dirigés en Colombie-Britannique. M.C. Feller 126

Des restrictions institutionnelles affectent la variabilité des coûts de brûlages dirigés. Découvete préliminaires. A. Gonzàlez-Cabàn et L.F. Bednar 136

La résponse des éléments nutritifs du sol et de l'ensemencement des pignons face à l'importance d'un feu. M.G. Harrington 143

Modélisation de la propagation vers le bas de la chaleur d'un feu dans des sols et du tissu végétal. R.D. Hungerford 148

Consumation de combustibles lors d'un brûlage dirigé de déchets de coupe dans le nord de l'Idaho. E.D. Reinhardt, J.K. Brown et W.C. Fischer 155

Taux de survie et croissance ultérieure de jeunes pins du sud soumis à un roussissement simulé des cimes. D.R. Weise, D.D. Wade et R.W. Johansen 161

SÉANCE 3: EFFETS DES CHANGEMENTS CLIMATIQUES

Régulateur: John Powell, Forêts Canada, Centre forestier du Nord, Edmonton, Alb.

EXPOSÉ PRINCIPAL: Changement climatique et incendie de forêt dans les forêts de conifères du Nord: scénarios de changement climatique. R. Wein 169

Mise à jour sur le changement climatique. J.B. Harrington 170

Modifications des apports du climat à la forêt boréale de l'ouest du Canada. E. Wheaton et J.A. Thorp 171

Les changements climatiques et les incendies de forêt en Ontario. R.B. Street 177

SÉANCE 4: GESTION DE LA FUMÉE ET QUALITÉ DE L'AIR
Régulateur: B. Stocks, Forestry Canada,
Great Lakes Forestry Centre, Sault Ste. Marie, Ontario

EXPOSÉ PRINCIPAL: La gestion de la fumée et la qualité de l'air.
W.T. Sommers 183

Les substances toxiques aériennes et l'exposition du personnel
travaillant à la ligne de feu. D.E. Ward 184

Système automatique de gestion de la fumée. R. Gilbert 194

SÉANCE 5: LA SANTÉ DES FORTÊS ET LA PRODUCTIVITÉ
Régulateur: Paul Addison, Forêts Canada, Direction générale des
sciences forestières, Ottawa, Ont.

EXPOSÉ PRINCIPAL: Protéger la santé et la productivité de la forêt boréale.
D.C. MacIver 195

Prédiction du rendement en matière ligneuse pour les peupleraies.
J.P. Carpentier 200

SÉANCE 6: COMPORTEMENT DU FEU ET DANGERS
Régulateur: Pat Andrews, USDA Forest Service, Intermountain
Fire Sciences Lab., Missoula, Mont.

EXPOSÉ PRINCIPAL: Prévision du comportement des feux de cime dans
une forêt de conifères. C.E. Van Wagner 207

Un modèle pour la saison des incendies basé sur les conditions météorologiques
A.J. Simard, J.E. Eenigenburg et W.A. Wein 213

Un modèle du processus de Markov d'un indice d'évaluation du danger
d'incendie de forêt. D.L. Martell 225

Applicabilité de la méthode canadienne d'évaluation des dangers d'incendie
de forêt dans le territoire du bureau d'aménagement forestier de Daxinganting
de la province de Heilongjiang en Chine. T.J. Lynham et B.J. Stocks 232

Évaluation au champ d'un modèle de teneur en humidité des résidus
d'exploitation de grosseur moyenne. B.D. Lawson et B.C. Hawkes 247

Influence de la compacité et de la teneur en eau et en matières inorganiques
du combustible sur la chaleur dégagée par un feu couvant dans la tourbe.
W.H. Frandsen 258

Comportement et effets du feu dans les peuplements de peupliers faux-tremble
-de feuillus du nord. M.E. Alexander et R.W. Sando 263

Modifications du système national de détection de dangers d'incendie
de 1978. R.E. Burgan 275

Limites de la combustion couvante dans la tourbe telles qu'influencées
par la teneur en humidité, la teneur en sol minéral et la densité apparente
de la matière organique. R.A. Hartford 282

Opposition entre la vitesse de propagation du feu prédite et celle observée
dans des lits de combustibles de pin ponderosa: une comparaison de la
méthode canadienne et du système américain. R.S. McAlpine et G. Xanthopoulos 287

Modélisation du comportement diurne de la teneur en humidité du combustible léger. D.F. Potts et G.A. Morris 295

La dynamique hydrique de la tourbe decoule de la recharge souterraine. P.G. Rivard, R.L. Rothwell et P.M. Woodard 298

SÉANCE 7: GESTION DES INCENDIES
Régulateur: Bob Bailey, Territorial Forest Fire Centre, Dept. of Renewable Resources, Fort Smith, T.N.-O.

EXPOSÉ PRINCIPAL: Mieux sinformer pour mieux protéger. R. Proulx 303

Mise en application d'un système d'information sur la gestion des incendies sur PC au Nouveau-Brunswick. W.G. Clowater, I.R. Methven et U. Feunekes 308

Intégration de systèmes d'information géographique à la gestion des feux de forêt. L.A. Salazar et C.V. Nilsson 311

Applications du modèle de simulation du taux d'accroissement d'un incendie en gestion des feux de forêt. P.L. Andrews 317

Élaboration d'un réseau automatique de prévisions horaires météo-incendie et son application à la gestion des incendies en Colombie-Britannique. S.K. Grimaldi et V.E. Fletcher 322

Protection des forêts contre le feu en Bulgarie, rendre les forêts moins combustibles. Y. Kurpanov 325

Transfert de technologie en Saskatchewan: utilisation opérationnelle de la méthode canadienne d'évaluation des dangers d'incendie de forêt. W.J. DeGroot 327

Effet de la météo horaire sur les superficies incendiées dans le système PCF. U. Feunekes et I.R. Methven 333

Le Système de gestion en protection des forêts du Québec. J. Guenette 337

Application du SIG en protection des forêts contre le feu. R. van Wyngaarden et T. Grimes 338

Méthode d'analyse spaciale pour la planification de la prépartion à la lutte contre les incendies de forêt. B.S. Lee et K.R. Anderson 339

Détection des incendies à l'aide de satellites du NOAA-N. G. Stephens et M. Matson 346

Surveillance d'un incendie sévère survenu dans la région forestière de Daxinanlin en 1987 et étude des pertes après l'incendie à l'aide d'images satellitaires de télédétection. Yang Yun-gian et Li Quan-bin 351

BANQUET

EXPOSÉ PRINCIPAL: Une perspective historique de la foresterie au Canada. J.C. Mercier 356

SÉANCE 8: MÉTÉO-INCENDIE ET CLIMAT

Régulateur: Ben Janz, Alberta Forestry Service, Provincial Forest Fire Centre, Edmonton, Alb.

EXPOSÉ PRINCIPAL: Antécédents climatiques et conditions météorologiques de l'incendie sévère de forêt de Daxinanlin de 1987 survenu en Chine. Yang Yun-qian et Jin Ji-zhong 364

Utilisation de modèles de prévision numérique de la météo pour la prévision à moyenne longue échèlle de la forêt-météo. K. Veyoshiet et J.O. Roads 377

Interpolation spatiale des prévisions des dangers de feu en terrain complexe da la Californie. M.H. McCutchan et T.H. Tsou 384

Prévisions de la "flambée explosive" d'un feu de friche. B.B. Aronovitch 391

Méthode de prévisions des précipitations pour le calcul des indices canadiens Forêt-Météo. L. Pouliot 400

Variation saisonnière de la teneur en humidité du combustible vivant du sous-étage d'une tremblaie de l'ouest des États-Unis. J.K. Brown, G.D. Booth et D.G. Simmerman 406

Circulation de l'eau dans les plantes ligneuses sous l'action de la chaleur: Résumé des résultats expérimentaux. W.B. Cohen et P.N. Omi et R.C. Rothermel 413

Analyse du comportement du feu associés à trois incendies de forêt du printemps 1988 survenus dans le centre du Canada. K.G. Hirsch 416

Caractérisation des anomalies moyennes mensuelles des éléments météorologiques favorables aux incendies à partir des anomalies concomitantes du champ de hauteur moyenne à 700 mb. W.H. Klein et B.T. Whistler 426

Relations entre les indices de danger mensuels moyens de feu et la gravité mensuelle des incendies. M.H. McCutchan et W.A. Main 430

L'application d'un système à base d'un micro-ordinateur au support forêt-météo. B. Snyder 436

Programme de prévisions forêt-météo R. Winterer 440

Adresses des auteurs 446

Voyage de familiarisation - technologie de peuplier hybride 453

Addresses des exposants commerciaux 454

Photos 455

Foreword

The Tenth Conference on Fire and Forest Meteorology was jointly sponsored by the Canadian Atmospheric Environment Service (Environment Canada), Forestry Canada, ministère de l'Énergie et des Ressources du Québec and the Ontario Ministry of Natural Resources. The conference theme was "Fire and Forest Meteorology in a changing environment: new technologies and concerns". This theme was timely as we live in a world of increasing change. The practice and our understanding of fire and forest meteorology is changing rapidly because of new technology and with new technologies comes new concerns.

Over 70 oral and interactive presentations were made in sessions on: Lightning and Forest Meteorology, Prescribed Burning and Fire Effects, Climate Change, Smoke Management and Air Quality, Forest Health and Productivity, Fire Behavior/Danger, Fire Management and Fire Weather/Climate. Our luncheon speaker, Dr. Sallie Gordon from the University of Idaho talked about the interaction between people and new technology. She highlighted many pitfalls that may occur if the human resource is not considered when changes are instituted. Our banquet speaker, Jean Claude Mercier, the Deputy Minister of Forestry Canada gave us an entertaining talk on the history and role of forestry in Canada. In addition, we were treated to a half-day field trip hosted by the Eastern Region of the Ontario Ministry of Natural Resources that gave us a first hand look at forestry in Eastern Ontario.

Several milestones were achieved at this Conference. It was the first time the conference was held in Canada and all presentations were simultaneously interpreted in both official languages (French and English). For the first time, exhibits from commercial vendors were an important part of the conference. Interactive presentations using posters, computers and video equipment were an integral part of the conference. Lastly, presentators from many different countries made this a truly international conference.

We are indebted to many people and organizations including the moderators and keynote speakers, sponsors and cooperators, commercial exhibitors, field tour guides and to all of our support staff (registration desk and audio-visual). In particular, we are grateful for the work of our various conference Secretariat members who worked countless hours to make the Tenth conference the success that it was.

We look forward to the Eleventh Conference on Fire and Forest Meteorology that will be held in Missoula, Montana in 1991.

Co-Chairs.

CONFERENCE SECRETARIAT

PROGRAM

M. Flannigan
L. Pouliot

COMMERCIAL EXHIBITS

P. Ward

LOCAL ARRANGEMENTS

D. Dubé

PUBLICITY

D. McRae

EDITORS

D. MacIver
H. Auld
R. Whitewood

COMPTROLLER/REGISTRAR

R. Street
D. MacIver

M. Flannigan
Co-Chair

P. Woodard
Co-Chair

Avant-propos

La dixième Conferérence sur l'incendie et météorologie forestière a été parrainée conjointment par le Service d'Environnement atmosphérique (Environnement Canada), Forêts Canada, le ministère de l'Énergie et des Ressources du Québec et le ministère des Richesse naturelles de l'Ontario. Le thème de la conférence était "L'incendie et météorologie forestière dans un environnement changeant: technologies et questions relatives". Ce thème est à-propos, car nous vivons dans un monde qui change constamment. La pratique et nos expériences acquises concernant l'incendie et la météorologie forestiers changent aussi, puisque de nouvelles technologies révèlent de nouvelles questions.

Plus de 70 présentations orales accompagnées de discussions traîtaient les sujets suivants: Foudre et météorologie forestière; Brûlage dirigé et effets du feu; Changements climatologiques; Gestion de la fumée et qualité de l'air; Santé des arbres et productivité forestière; Dangers et comportement du feu; Gestion des incendies en forêts et climat/temps de feu de forêt. Notre conférencière, Dr. Sallie Gordon de l'Université d'Idaho, a parlé, lors du déjeuner, de l'intéraction entre les gens et la technologie. Elle a souligné les pièges qui pourraient survenir si l'on ne prenait pas en considération les ressources humaines au cours des changements introduits. Le conférencier du banquet, M. Jean Claude Mercier, sous-ministre de Forêts Canada, nous a décrit de façon divertissante l'histoire et le rôle de la foresterie au Canada. En outre, on nous a offert une excursion d'un demi-jour sur le terrain, organisée par le ministère des Richesses naturelles de l'Ontario. Ainsi, nous avons eu un aperçu des activités forestières à l'est de l'Ontario.

Plusieurs jalons ont augmenté l'importance de ce rassemblement. C'était la première fois, que cette conférence a eu lieu au Canada et que toutes les présentations ont été interprétées simultanément dans les deux langues officielles (en français et en anglais). Pour la première fois également, les expositions des représentants commerciaux ont fait partie significative de la conférence. Les présentations des affiches, des équipements d'ordinateur et des matériels vidéo ont formé les cadres intégrants. Enfin, la participation des conférenciers venus de nombreux pays a souligné le vrai caractère international de cette conférence.

Nous sommes extrêmement reconnaissants à un grand nombre de personnes et d'organisations, y compris les présidents, les conférenciers, ceux et celles qui ont parrainé la conférence, les coopérants, les exposants commerciaux, les guides et tout le personnel de soutien (à l'accueil et à la section d'audio-visuel). Nous remercions particulièrement les membres du Secrétariat d'avoir autant travaillé pour la réussite qu'elle était cette dixième conférence.

Nous attendons donc la onzième Conférence sur l'incendie et météorologie forestière qui sera tenue à Missoula, au Montana en 1991.

co-présidents

SECRÉTARIAT DE LA CONFÉRENCE

PRÉSIDENTS DU PROGRAMME	COORDINATEUR DES EXPOSANTS COMMERCIAUX	DISPOSITIONS SUR PLACE
M. Flannigan L. Pouliot	P. Ward	D. Dubé

COORDINATEUR DE LA PUBLICITE	ÉDITEURS	AMINISTRATEUR/ACCUEIL
D. McRae	D. MacIver H. Auld R. Whitewood	R. Street D. MacIver

M. Flannigan
Co-président

P. Woodard
Co-président

Welcoming Remarks

H.L. FERGUSON
Assistant Deputy Minister, Atmospheric Environment Service,
Environment Canada

Thank you Mr. Chairman. Ladies and gentlemen, it is my pleasure to welcome you to this 10th Conference on Fire and Forest Meteorology, and to its first meeting in Canada. To those of you visiting Ottawa and perhaps Canada for the first time, I extend a special welcome. I hope you will have an opportunity during your stay to tour our nation's capital and enjoy its hospitality. The conference organizers have provided us with a wealth of information in the form of pamphlets and brochures, and no doubt would be delighted to provide any further assistance you require in arranging tours or visits.

For many years, the Atmospheric Environment Service has provided both weather and climate services and information to assist in the protection of our forest resources. In fulfilling our mandate to meet the safety and security needs of Canadians, the Atmospheric Environment Service has a long history of providing support to fire fighting agencies. We are proud of the high level of co-operation among federal and provincial agencies, which can serve as a model for increased interactions in future.

On the longer climate horizon, increased international co-operation has been stimulated during the 1980s by a series of scientific meetings where concerns for present and future atmospheric conditions were voiced. Meetings in 1985 and 1987 in Helsinki, Finland, Villach, Austria, and Bellagio, Italy, identified concerns for sulphur dioxide emissions and greenhouse warming. The Montreal Protocol of 1987, and subsequent events, have committed many nations of the world to dramatic cuts in production of chlorofluorocarbons which destroy stratospheric ozone as well as contributing to the accelerating greenhouse effect.

Last year, Toronto was host to two major international meetings. The first was the Economic Summit meeting of the seven leading industrialized nations of the world where the 1987 Brundtland Commission's philosophy of environmentally sustainable global socio-economic development was endorsed. The second was the Changing Atmosphere conference sponsored by the Canadian government. This conference addressed such issues as greenhouse gases, atmospheric pollution, monitoring networks, research programs, acid rain, arctic pollution and protection of the stratospheric ozone layer. As a followup, the Canadian government has instituted a series of so-called "round tables". These consist of national and regional planning meetings of government and industry representatives to make recommendations on how natural resources can be wisely used in such a way that supplies are sustained for future generations.

The results of all of these important international conferences may eventually be reflected in a global framework Convention to protect the atmosphere. Canada first began advocating such an international understanding in 1986. The proposed Convention would recognize the need for all countries to address the problem of taking greater care of one part of our shared Global Commons--the atmosphere. It would be a basic legal document to which could be attached, over time, individual protocols dealing with such unique and important issues as greenhouse gases, acid rain, and the systematic early international warning of major environmental accidents such as Chernobyl.

The scientific basis for concerns expressed at these several international meetings stems from the outputs of several highly sophisticated, computerized global climate simulation models. These models strongly suggest that global atmospheric average warming in the order of 1.5 to 4.5 degrees celsius should be anticipated within the next 50 years, with even greater warming in higher latitude regions, such as the boreal forest region of Canada. As a result, we can expect significant changes to the forest resource base, and anticipate profound impacts on Canadian forest industries.

This relatively very rapid warming trend, accompanied by increased climatic variability, could result in an increase in the frequency, duration and severity of events of thermal and moisture stress, forest fires, and insect and disease infestations. Such major impacts will necessitate creative planning and decision-making in order to retain our competitive position in the international marketplace. The climate warming scenarios need to be introduced now into forest planning strategies, considering that it can take several decades to grow a Canadian tree.

What policy options do we have available? On the global scale, the first must surely be to reduce emissions which are harmful to both humans and their forests. In addition to the issues of acid precipitation, stratospheric ozone depletion and forest dieback, the problems associated with fire management must be appropriately dealt with, from the perspectives of both smoke management impacts on human health and emissions of carbon dioxide into the atmosphere.

Secondly, our efforts should be holistic, based on a multi-media ecosystem approach to research and monitoring and focused toward better understanding the relationships between climate, various tree species and their surrounding environment. Once these relationships are more fully understood, we will be in a better position to detail the likely impacts of climate change on forests, forest ecosystems and forest industries.

Last year, the Atmospheric Environment Service established a new Centre for Atmospheric Research Experiments north of Toronto. At this site, comprehensive integrated monitoring and modelling of atmospheric, vegetation and soils characteristics are being initiated. Co-operative studies with other federal and provincial agencies, universities and the private sector will be conducted in an effort to better understand the complex cause-and-effect relationships among the several components of the biosphere.

On a global scale, the forests of North America play a significant role as a sink for atmospheric carbon. Given the rate of deforestation in other parts of the globe, the North American role is all the more important, and Canadian and American efforts in forest regeneration should be enhanced.

Day-by-day co-operation is not new to the fire community. Local, national and international co-operation to face the challenges of atmospheric changes will be essential if we are to minimize new climatically imposed constraints and maximize benefits. Again, welcome to Canada and to Ottawa. To all participants at the Conference, let me extend an invitation to visit us again, and may you have a successful meeting. Thank you.

Allocution de Bienvenue

H.L. FERGUSON
Sous-ministre adjoint, Service de l'environnement atmosphérique,
Environnement Canada

Merci Monsieur le Président. Mesdames et Messieurs, c'est pour moi un immense plaisir de vous souhaiter la bienvenue à ce dixième colloque sur les incendies de forêt et la météorologie forestière, le premier à se dèrouler au Canada. Je transmets mes souhaits les plus chaleureux à ceux qui ne sont jamais venus à Ottawa, voire au Canada. J'espère que vous aurez l'occasion de visiter la capitale de notre pays durant votre séjour et d'apprécier l'hospitalité de ses habitants. Les organisateurs du colloque nous ont remis une foule de documentation sous forme de dépliants et de brochures et sans aucun doute seront heureux de vous prêter main-forte pour les visites ou les excursions.

Depuis longtemps déjà, le Service de l'environnement atmosphérique offre des services climatologiques et météorologiques et diffuse de l'information afin de mieux protéger nos ressources forestières. Sur les plans pratique et quotidien, l'Indice de danger du feu, un des six indices utilisés dans le cadre du système canadien de prévision des dangers d'incendie forestier, a été créé par le Service de l'environnement atmosphérique qui continue de l'utiliser. Dans le cadre de notre mandat, qui consiste à répondre aux besoins de sécurité des Canadiens, nous prêtons depuis longtemps assistance aux combattants du feu. Nous sommes d'ailleurs très fiers de l'étroite collaboration qui existe entre les organismes fédéraux et provinciaux, collaboration susceptible de servir de modèle en vue d'interactions plus rapprochées dans l'avenir.

En ce qui concerne la situation climatique à plus longue échéance, on a assisté à un regain de la coopération internationale au cours des années 1980 consécutivement à une série de colloques scientifiques au cours desquels se sont exprimées les craintes relatives aux conditions atmosphériques existantes et futures. Les recontres de 1985 et de 1987 à Helsinki, en Finlande, à Villach, en Autriche, et à Bellagio, en Italie, ont contribué à préciser nos appréhensions sur les émissions de dioxyde de soufre et le réchauffement dû à l'effet de serre. Le protocole ratifié à Montréal en 1987 et les événements qui ont suivi ont incité beaucoup de pays à réduire de façon draconienne leur production de chloroflurocarbones, ces composés qui détruisent l'ozone dans la stratosphère et exacerbent l'effet de serre.

L'an dernier, Toronto a été le site de deux rencontres internationales exceptionnelles. Lors de leur sommet économique, les Sept Grands ont souscrit sans réserves à la philosophie de la Commission Brundtland qui, en 1987, préconisait un développement socio-économique durable dans le monde au point de vue de l'environnement. La deuxième était le colloque "L'atmosphère en évolution" parrainé par le gouvernement du Canada. Les participants à ce colloque se sont penchés sur diverses questions comme les gaz responsables de l'effet de serre, la pollution de l'air, les réseaux de surveillance, les programmes de recherche, les pluies acides, la pollution de l'Arctique et la protection de la couche d'ozone dans la stratosphère. Par la suite, le gouvernement canadien a lancé une série de "tables rondes" consistant essentiellement en séances de planification nationales et régionales où des représentants du gouvernement et du secteur privé ont formulé des recommandations sur la façon d'exploiter avec sagesse les ressources naturelles afin de les préserver pour les générations à venir.

Toutes ces rencontres internationales d'importance capitale pourraient déboucher tôt ou tard sur l'adoption d'une convention-cadre sur la protection de l'atmosphére. Le Canada a d'ailleurs proposé l'adoption d'une telle entente en 1986. La convention envisagée reconnaîtrait que tous les pays doivent s'attaquer plus sérieusement au problème qui consiste à prendre soin d'une partie de ce patrimoine commun qu'est l'atmosphère. Il s'agirait d'un texte juridique fondamental auquel s'annexeraient, avec le temps, des protocoles distincts sur des problèmes majeurs, mais particuliers comme les gaz à l'origine de l'effet de serre, les pluies acides et un système d'alerte international automatique lorsque surviennent de graves accidents environnementaux comme celui de Chernobyl.

Les craintes exprimées à l'occasion de ces diverses rencontres ont pour base scientifique des modèles de simulation informatiques ultra-sophistiqués sur le climat global. Ces modèles laissent fortement entrevoir un réchauffement moyen de l'atmosphère terrestre de l'ordre de 1,5 à 4,5 degrés Celsius au cours des 50 prochaines années, avec accentuation de ce réchauffement dans les régions à haute latitude comme la forêt boréale canadienne. On peut donc s'attendre à d'importants bouleversements au niveau des ressources forestières, avec la profonde incidence que cela aurait sur l'industrie canadienne.

Cette tendance vers un réchauffement relativement rapide et une variabilité accrue du climat pourrait accroître la fréquence, la durée et la gravité des épisodes de stress thermique et hydrique, des feux de forêt et des infestations d'insectes ou des épidémies. Pareilles conséquences exigeront une planification et des décisions inventives si l'on veut que le Canada maintienne sa position concurrentielle sur le marché international. On doit d'ores et déjà intégrer le réchauffement du climat aux stratégies en matière d'aménagement forestier, puisqu'il faut plusieurs décennies à un arbre pour parvenir à maturité au Canada.

Quelles sont nos options? À l'échelon global, la première consiste assurément à réduire les émissions qui détériorent la qualité de la vie et les forêts. Outre les problèmes de la précipitation acide, de l'appauvrissement de la couche d'ozone et du dépérissement des forêts, il faut s'attaquer aux difficultés connexes à la gestion du feu, tant en ce qui concerne l'incidence de la fumée sur la santé que les émissions de dioxyde de carbone dans l'atmosphère.

En second lieu, il faudrait déployer des efforts holistiques, articulés sur une approche multimédia de l'écosystème sur le plan de la recherche et de la surveillance, de même que parvenir à une meilleure compréhension des liens qui existent entre le climat, les diverses espèces d'arbre et le milieu qui les entoure. Quand ces liens seront mieux compris, nous serons plus en mesure de cerner l'impact probable d'un changement du climat sur les forêts, l'écosystème forestier et l'industrie du bois. L'an dernier, le Service de l'environnement atmosphérique a créé un nouveau centre de recherches et d'expériences sur l'atmosphère au nord de Toronto où se poursuivent des essais complexes sur un système intégré de surveillance et de modélisation des paramètres relatifs à l'atmosphère, à la végétation et au sol. Des études entreprises en collaboration avec d'autres organismes fédéraux et provinciaux, des universités et le secteur privé s'y dérouleront pour nous aider à mieux comprendre les complexes relations causales qui existent entre les différents éléments de la biosphère.

Les forêt d'Amérique du Nord jouent un rôle déterminant sur le plan mondial, en absorbant le trop-plein de carbone présent dans l'atmosphère. Face à la rapidité du déboisement dans d'autre régions du globe, ces forêts verront leur importance grandir sans cesse. Violà pourquoi il faut accélérer le reboisement au Canada et aux Ètats-Unis.

La coopération quotidienne n'est pas chose nouvelle chez les combattants du feu. Toutefois, une coopération locale, nationale et internationale s'avérera nécessaire si on veut relever le défi du changement de l'atmosphère et minimiser les nouvelles contraintes imposées par le climat, tout en en maximisant les avantages. Encore une fois, bienvenue au Canada et à Ottawa. Je me permets de convier tous les participants à revenir nous voir et leur souhaite le plus grand succès dans leurs travaux. Je vous remercie de votre attention.

Welcoming Remarks

J.C. MERCIER
Deputy Minister, Forestry Canada

Good evening Ladies and Gentlemen. I am indeed pleased to have the opportunity, on behalf of the government of Canada and Forestry Canada, to welcome you to Ottawa, our national capital, and the 10th Conference on Fire and Forest Meteorology.

I wish to recognize the Atmospheric Environment Service, ministere de l'Énergie et des Ressources du Quebec and the Ontario Ministry of Natural Resources, our co-sponsors of this important and vital conference. It is a great pleasure to work directly and cooperatively with you in this endeavour.

Many of you may be visiting Canada, or this part of Canada, for the first time. We will do all we can to ensure that your visit is a pleasant and memorable one. I'm sure the conference organizers intend to mix some pleasure with the important business that you are here to conduct over the next few days.

I am advised that this is the twenty-second anniversary of this prestigious, bi-annual conference, and that this is the first time that we, in Canada, have had the opportunity to host it. We hope, in some small way, to reciprocate the gracious and considerate treatment we always receive from our American friends and colleagues during our visits stateside.

Meeting with the fire community is always a rewarding experience for me. I am continually impressed by the close ties the fire community has forged between researchers and operational personnel at regional, national and international levels.

To a considerable extent the nature and seriousness of the wildland fire problem, facilitates, indeed necessitates, close cooperation. I suspect that you may well take these close associations for granted, but let me assure you, it is a unique partnership. Many other forestry disciplines would do well to achieve similar levels of cooperation and communication. Let me elaborate.

In Canada, the Canadian Committee on Forest Fire Management held its 37th Annual Meeting in January of this year. This is an enviable record of continuing collaboration by senior fire management and research personnel from provincial, territorial, federal, educational and private organizations.

More recently, the Canadian Inter-Agency Forest Fire Centre (CIFFC) has been established to facilitate sharing of personnel and equipment between Canadian fire management agencies. CIFFC administers the Mutual Aid Resource Sharing Agreement which allows this country to maintain a national air tanker fleet of 14 CL-215s in addition to the 35 CL-215s owned and operated by six provinces and two territories.

The Canada/U.S. Forest Fire Fighting arrangement is also administered by CIFFC and its U.S. counterpart NIFC, the National Interagency Fire Centre. This arrangement allows fire personnel and millions of dollars worth of fire equipment to cross our respective borders without delay in response to emergency fire situations. It has served both our countries well in recent years.

Regionally, several forest fire management arrangements exist between states and provinces, such as the Great Lakes Forest Fire Compact and the North-East Forest Fire Protection Commission that facilitate greater cooperation.

Virtually all provinces, territories and parks in Canada have formalized inter-border agreements that allow quick dispatch and action on near-border fires, without worrying about which side of the line the fire is on. You have agreed to sort out the paper work later.

Forest fire research has an equally impressive record of cooperation. Forestry Canada fire researchers, widely scattered across the country, have for many years, banded together to conduct fire behaviour field research experiments such as those at Darwin Lake, Alberta and Porter Lake in the North West Territories.

These projects are an integral part of a larger forestry Canada national program, manifested in the flagship of Canadian Forest Fire Research, "The Canadian Forest Fire Danger Rating System". This system is currently used by all forest fire management agencies in Canada and is gaining international recognition and acceptance as well.

In Forestry Canada, we recognize the vital importance of effective transfer of our research results. One of our fire research units at the Petawawa National Forestry Institute has worked closely with the Societe de Conservation de l'Outaouais, a Quebec Fire Management Agency, for over 25 years. This mutual effort has resulted in the successful development and implementation of one of the most advanced and automated fire management systems in the world.

At the international level many of you are aware of the Canada/U.S. cooperative mass fire behaviour and atmospheric environmental impact study.

This study, involving several Canadian and American agencies, has major implications for assessing atmospheric quality, particularly as it relates to the use of prescribed fire as a forest management tool.

I doubt this study could have been successfully initiated without the longstanding, productive associations you have carefully nurtured as a forest fire community. Today, that effort is bearing fruit.

Finally, the fire community has put in place an on-going, series of workshops sponsored by such groups as the Interior West Fire Council, the Northwest Fire Council and others, and conferences such as this one.

These forums allow you to objectively monitor your progress and accomplishments on an annual or bi-annual basis and exchange fresh ideas and ways of doing business.

This conference represents a fertile benchmark of your present knowledge, creativity and inventiveness and serves as a springboard to new goals and visions.

Your accomplishments, credibility and reputations have reached the ears of the world. More and more, Canadian and U.S. fire research and management experts are being called upon to assist other nations. This is a challenge that you must accept as we come to understand that we live in a global community and have global responsibilities. Yet, while responding to international needs, we must continue to effectively protect our own forests and wildland.

I have spoken enough of your accomplishments without fear of creating any sense of complacency as I know that the tasks ahead will challenge you even further.

I wish you well in your deliberations and look forward to visiting with many of you over the next few days.

Thank you and good night.

Allocution de Bienvenue

J.C. MERCIER
Sous-Ministre, Forêts Canada

Bonsoir Mesdames et Messieurs. Je suis très heureux d'avoir l'occasion, au nom du gouvernement canadien et de Forêts Canada, de vous souhaiter la bienvenue à Ottawa, notre capitale, et à ce 10e colloque sur les feux de forêt et la météorologie forestière.

J'aimerais avant tout remercier le Service de l'Environnement atmosphérique, le Ministère de l'Énergie et des Ressources du Québec ainsi que le Ministère des Richesses naturelles de l'Ontario qui ont coparrainé ce colloque d'importance capitale. Pouvoir travailler directement et de concert avec pareils organismes dans une telle entreprise s'est avéré un véritable privilège.

Il se peut que beaucoup d'entre vous soient au Canada ou, du moins dans cette partie du Canada, pour la première fois de votre vie. Soyez assurés que nous ferons tout notre possible pour que ce séjour soit aussi plaisant que mémorable. Je suis persuadé que les organisateurs du colloque ont l'intention de joindre l'utile à l'agréable, l'utile étant bien sûr l'important travail que vous accomplirez au cours des quelques prochains jours.

On m'a signalé qu'il s'agissait du vingt-deuxième anniversaire de ce prestigieux colloque semestriel, que le Canada a pour la première fois l'occasion d'accueillir. J'espère que nous pourrons, dans une certaine mesure, rendre la pareille à nos amis et collègues américains qui nous reçoivent si amicalement lors de notre passage dans leur pays.

Rencontrer d'autres membres de la grande famille des combattants du feu a toujours été pour moi une expérience enrichissante. Je suis continuellement impressionné par les liens étroits que la lutte contre les incendies en forêt noue entre les chercheurs et le personnel sur le terrain aux échelons régional, national et international.

Dans une très grande mesure, la nature et la gravité du problème du feu dans les étendues sauvages favorisent, voire exigent une étroite collaboration. Sans doute jugez-vous normaux des contacts aussi étroits. Laissez-moi vous assurer qu'il s'agit là d'un cas tout à fait particulier. Beaucoup d'autres disciplines connexes à la foresterie retireraient beaucoup d'un tel degré de coopération et de communication. Je m'explique.

En janvier dernier, le comité canadien de gestion des feux de forêts tenait sa 37e assemblée annuelle. Ceci témoigne d'une longue collaboration entre gestionnaires et chercheurs supérieurs du feu au sein des organisations provinciales, territoriales, fédérales, pédagogiques et privées, collaboration qui mérite d'être applaudie.

De création plus récente, le centre interservices des feux de forêt du Canada facilite le partage du personnel et du matériel entre les organismes canadiens pertinents. Le centre administre l'accord d'aide mutelle en cas d'incendie de forêt qui nous permet de garder une escadrille nationale de 14 avions-citernes cl-215s, auxquels il faut ajouter les 35 cl-215s, propriété des six provinces et des deux territoires qui les exploitent.

Le centre administre également l'accord sur la lutte contre les feux de forêt conclu entre le Canada et les États-Unis, en collaboration avec l'organisme américain analogue, le National Interagency Fire Centre. Cet accord permet aux combattants du feu et à un matériel d'une valeur de plusieurs millions de dollars de franchir la frontière sans délai en cas d'urgence. Les deux pays en ont d'ailleurs profité abondamment au cours des quelques dernières années.

À l'échelon régional, les états et les provinces sont parvenus à plusieurs ententes sur la lutte contre les feux de forêt. Je pense notamment au Great Lakes Forest Fire Compact et à la North-East Forest Fire Protection Commission qui ont contribué à étendre la coopération à cet égard.

Pratiquement tous les parcs du Canada, comme les territoires et les provinces, ont signé des ententes transfrontière officielles en vue d'une action rapide lorsqu'un feu de forêt se déclare en bordure des limites territoriales, sans qu'on ait à s'inquiéter de quel côté de la ligne le brasier fait rage. Les questions de paperasse sont réglées plus tard.

La coopération semble également servir de mot d'ordre dans la recherche sur les feux de forêt. Les chercheurs de Forêts Canada, qui sont disséminés dans tous les coins du pays, ont depuis longtemps fait front commun pour procéder aux expériences sur le terrain qui permettent de mieux cerner le comportement du feu, comme au lac Darwin, en Alberta, ou au lac Porter, dans les Territoires du Nord-Ouest.

Ces projets font partie intégrante d'un plus vaste programme national, dirigé par Forêts Canada, dont la "méthode canadienne d'évaluation des dangers d'incendie de forêt"; le porte-étendard de la recherche canadienne sur les feux de forêt. À l'heure actuelle, tous les organismes de lutte contre le feu du Canada appliquent cette méthode qui attire également de plus en plus l'attention de la collectivité internationale.

Forêts Canada admet le rôle déterminant d'un bon transfert des résultats expérimentaux. Ainsi, un de nos services de recherche sur le feu de l'institut forestier national de Petawawa travaille en étroite collaboration avec la société de conservation de l'Outaouais, un organisme québécois de lutte contre les feux de forêt, depuis plus de 25 ans. Leurs efforts mutuels ont débouché sur l'élaboration et la mise en oeuvre d'un des systèmes de lutte contre les incendies de forêt automatiques les plus perfectionnés du monde.

À l'échelon international, beaucoup d'entre vous sont au courant de l'étude conjointe que le Canada et les États-Unis ont entreprise sur le comportement des incendies de grande étendue et l'incidence de ces derniers sur l'environnement atmosphérique.

Cette étude qui exige le concours de plusieurs organismes canadiens et américains s'avérera particulièrement utile pour déterminer la qualité de l'air ambiant, surtout lorsqu'on envisage se servir du brûlage dirigé pour l'aménagement forestier.

Je doute fort qu'on soit parvenu à la mettre en oeuvre sans les liens fructueux qui rattachent depuis longtemps les combattants du feu et qui ont été si amoureusement préservés au sein de cette collectivité. Vos efforts sont maintenant récompensés.

Enfin, la collectivité que vous représentez a lancé une série permanente d'ateliers que parrainent divers groupes comme l'Interior West Fire Council, le Northwest Fire Council et bien d'autres ateliers qui s'ajoutent aux colloques comme celui-ci.

Pareilles rencontres vous permettent d'établir de façon objective les progrès réalisés au bout de six mois à un an, ainsi que d'échanger des idées et de nouvelles façons pour les mettre en pratique.

Ce colloque constituera une mise au point fort utile sur les connaissances existantes, de même que notre créativité et ingéniosité, et nous servira de tremplin en vue de la réalisation de nouveaux objectifs ou de la matérialisation de nouvelles visions.

Vos réalisations, votre crédibilité et votre réputation ont fait le tour du monde. De plus en plus, les spécialistes canadiens et américains de la recherche et de la lutte contre les incendies de forêt reçoivent des appels à l'aide d'autres pays. Ce défi, nous devrons le relever, car nous prenons peu à peu conscience que nous vivons dans une communauté globale et que nos responsabilités s'étendent à l'ensemble de la planète. Néanmoins, tout en répondant aux besoins internationaux, nous devrons veiller à protéger efficacement nos forêts et nos étendues sauvages.

Assez parlé de vos réalisations. Poursuivre serait une incitation à la complaisance et je sais que les tâches qui vous attendent sauront vous motiver encore plus.

Je vous souhaite donc le plus franc succès dans vos délibérations et espère avoir l'occasion de revoir beaucoup d'entre vous au cours des quelques prochains jours.

Je vous remercie de votre attention et vous souhaite une bonne soirée.

Welcoming Remarks

R. J. BURGAR
Assistant Deputy Minister, Ontario Ministry of Natural Resources

Good evening ladies and gentlemen. On behalf of the Ontario Ministry of Natural Resources, I'd like to welcome you to the Tenth Conference on Fire and Forest Meteorology. May I offer a special greeting to those of you who are visitors to Ontario.

As you know, the theme of this particular conference is "Fire and Forest Meteorology in a Changing Environment -- New Technologies and Concerns". That's a subject of particular interest to my Ministry, because in Ontario the Ministry of Natural Resources is charged both with forest management and fire management in those forests.

And for the past three years, we've experienced particularly severe fire seasons. As far as this year is concerned, at the moment we're experiencing a more typical spring fire season -- and we're hopeful that trend will continue for the rest of the fire season.

Judging from these past few fire seasons, it seems we've been visited by that ancient Chinese curse: "May you live in interesting times." Every year since 1986 has been more interesting than the last.

So we were very pleased not only to be able to host this conference, but also to get many of our own people here to attend.

The subjects of weather and climate, and their effects on forest health and forest fire conditions, have never been more topical. The whole concept of our changing environment is one that is increasingly in the public eye. Issues and events about the environment are making news around the world. Fifteen years ago, the general public had never even heard terms such as "climate change","Ozone depletion", and "Greenhouse effect". Today, you can't pick up a newspaper or listen to a broadcast without encountering at least one headline item about the environment.

We, as fire and forest managers, have a vested interest in the impacts of climate change, the greenhouse effect, jetstream anomalies, ocean current oscillations, and so on.

As fire managers, we're well versed in dealing with the immediate impact of changing weather patterns. But pity the poor forest managers. They have to make regeneration decisions now, even though their future forest crop could well mature in a significantly different climatic regime.

Now, that's what I call living in interesting times.

Here in Ontario, we've made some major studies in using new technologies to monitor, assess and predict environmental conditions -- especially as they relate to coping with forest fires. And as I mentioned earlier, the past three years have given us plenty of opportunity to practise what we've learned.

You'll be seeing some of these applications later this week in presentations by Ministry of Natural Resources staff.

Whether you're a forest manager or a fire manager, emerging technologies can help. In fire management, for example, the past decade has taught us a lot about predicting fire behaviour. In forest management, we've learned to use prescribed burning effectively.

Ultimately, we may never be advanced enough to actually control the weather -- but we can learn how to take full advantage of whatever we do get thrown at us.

You're here to talk about new technologies. Whether you're a forest manager or a fire manager, new technologies may well be the key to coping with living in interesting times.

I wish you a successful and instructional conference.

Allocution d'ouverture

R.J. BURGAR
Sous-ministre adjoint
Ministère des Richesses naturelles de l'Ontario

Bonsoir Mesdames et Messieurs. Au nom du ministère des Richesses naturelles de l'Ontario, j'aimerais vous souhaiter la bienvenue à ce dixième colloque sur les incendies de forêt et la météorologie forestière. Mes souhaits s'adressent tout particulièrement à ceux de passage dans cette province.

Le thème que vous avez retenu - les incendies de forêt et la météorologie forestière dans un milieu en pleine évolution: nouvelles techniques et nouveaux problèmes - intéresse tout spécialement le Ministère des Richesses naturelles de l'Ontario, car celui-ci s'occupe à la fois d'aménagement forestier et de gestion des incendies en forêt.

En outre, au cours des trois dernières années, les feux de forêt se sont montrés passablement destructeurs. Heureusement, cette année, nous connaissons des feux de forêt plus normaux pour le printemps, du moins jusqu'à présent. Il faut espérer que cette tendance se poursuivra durant la période la plus dangereuse.

Lorsqu'on examine les saisons de feux les plus récentes, on pourrait croire que le Canada a été frappé par l'antique malé-diction chinoise "Puissiez-vous vivre des temps INTÉRESSANTS". Et on peut l'affirmer, depuis 1986, chaque année s'est avérée plus INTÉRESSANTE que la précédente.

C'est pourquoi nous avons été très heureux non seulement de parrainer ce colloque, mais aussi d'y amener beaucoup de participants du Ministère.

Le temps et le climat et leur incidence sur l'état des forêts de même que sur les conditions propices aux incendies en forêt; ces sujets n'ont jamais été aussi pertinents. Le concept même d'un environnement en pleine évolution retient de plus en plus l'attention de la population. Tout ce qui touche l'environnement fait la manchette des journaux des quatre coins du globe. Il y a quinze ans, le grand public ignorait tout du "changement climatique", de "l'appauvrissement de la couche d'ozone", de "l'effet de serre". Aujourd'hui par contre, impossible d'ouvrir un journal ou d'écouter un bulletin d'information à la télévision sans entendre parler de l'environnement.

En tant qu'aménagistes forestiers et gestionnaires des incendies en forêt, il est normal que nous nous penchions sur les conséquences d'un changement de climat, de l'effet de serre, des anomalies observées au niveau de jet-stream, de l'oscillation des courants océaniques et le reste.

Ceux qui luttent contre les feux de forêt savent s'adapter aux répercussions immédiates des caprices de la température. Les aménagistes forestiers sont plus à plaindre, car ils doivent prendre des décisions en matière de régénération immédiatement, même si les forêts qu'ils plantent pourraient bien parvenir à maturité dans des conditions climatiques fort différentes.

Violà ce que j'appelle vivre des temps intéressants!

L'Ontario a accompli des progrès notables en recourant à de nouvelles techniques pour surveiller, évaluer et prévoir les conditions ambiantes, en particulier dans le cadre de la lutte contre les feux de forêt. Comme je l'ai indiqué précédemment, nous avons eu amplement l'occasion de mettre en pratique ce que nous avons appris au cours des trois dernières années.

Plus tard durant la semaine, les présentations du personnel du ministère des Richesses naturelles illustreront certaines de ces applications.

Les techniques de pointe peuvent vous aider, soit à aménager les forêts ou à lutter contre les incendies. Dans le second cas, par exemple, la dernière décennie nous a beaucoup appris sur la manière de prévoir le comportement du feu. En ce qui concerne l'aménagement forestier, nous avons appris à faire un usage efficace du brûlage dirigé.

En fin de compte, il est possible que nous ne progressions jamais assez pour devenir vraiment maîtres du climat. Cependant, nous pouvons apprendre à tirer le meilleur parti de la situation.

Vous êtes ici afin de parler de technologies de pointe. Que vous soyez aménagiste forestier ou gestionnaire du feu, ces technologies pourraient bien être la solution à la vie en des temps intéressants.

Je vous souhaite un colloque aussi agréable qu'instructif.

Welcoming Remarks

G. PAILLÉ
Deputy Minister
Quebec Ministère de l'Energie et des Ressources
presented by R. Proulx

Mr. Chairman, Distinguished Guests, Ladies and Gentlemen:

On behalf of the Québec Associate Deputy Minister for Forests, I wish to thank the organizers of the Tenth Conference on Fire and Forest Meteorology for inviting Mr. Gilbert Paillé to take part in this opening ceremony. Unfortunately, because of a prior commitment, Mr. Paillé is unable to be present this evening.

As one of the sponsors of the conference, the Ministère de l'Énergie et des Ressources would like to stress the importance of meteorology as applied to forest protection and forest fire management.

Québec operates a forest fire protection system that requires 28 million dollars annually to cover normal operations. In addition to this amount, extinguishing forest fires costs, on average, another 5 million dollars more. The practical result of all these expenses is an organization that includes specialized crews, aircraft and other equipment the province seeks to manage as effectively as possible.

For the time being, the performance of the system meets with the approval of both the government and the forest industry. However, it is to be expected that, in the future, pressure will be brought to bear to improve the general efficiency of fire protection. Indeed, the New Forest System, effective in the province since April 1, 1987, now imposes on forest industries well defined responsibilities concerning forest management.

These responsibilities must be assumed in compliance with the basic principle of our new Forest Act, that is, by respecting the allowable annual cut.

According to current estimates, forest management on the basis of the allowable annual cut will be carried out in a context of limited timber reserves. By April 1, 1990, once the 275 or so timber supply and forest management agreements are in effect, very few timber reserves will be left.

We simply cannot afford to risk endangering the entire new orientation through widespread destruction resulting from forest fires.

As in other areas of activity, sustained innovative effort is required to improve forest protection. Fortunately, the fast pace of technological change provides an opportunity to integrate the results of research and development more quickly and efficiently. I should like to share three instances of this fact in Québec.

First, over the past 15 years, there has been a genuine willingness to improve the quantity and quality of the information necessary to make daily decisions in detecting and fighting forest fires. In particular, close collaboration with the Petawawa National Forestry Institute has led to the successful testing of a modern information management system capable of supporting a centralized protection agency operating in the southwestern part of the province.

Second, information concerning weather conditions is obviously part of the basic information required for such a system. Besides obtaining the best possible weather forecast, another crucial need arises in forest protection: to know how precipitation is distributed over the territory. On this particular point, Québec, in conjunction with competent organizations, plans to thoroughly test the possibilities of a precipitation radar especially adapted to the specific requirements of fire protection.

Finally, we also realize that our forest fire danger evaluation and forecast system can be improved. Thus, in order to integrate new developments produced by research teams and product suppliers, we have asked the provincial protection organizations to prepare a master plan aimed at updating all the elements included in our forest weather forecast system.

The three preceding examples are evidence of Québec's eagerness to collaborate in the development of meteorology as applied to forest fires. We also wish to benefit from the efforts of other interested parties to improve forest protection. This week's conference is a good occasion to exchange ideas and shop around.

We must remember that progress and new techniques normally have an effect either on individual users or organizational structures. To achieve the greatest protection at the lowest price, we must, from time to time, reexamine these facts. That, I believe, is the main goal of this conference.

Mr. Gilbert Paillé, Québec's Associate Deputy Minister for Forests, has asked me to offer his best wishes for success in meeting their goal to the organizers and participants of this conference.

Allocution de bienvenue

G. PAILLÉ
Sous-ministère, Quebec Ministère de l'Energie et des Ressources
Présenté par R. Proulx

Monsieur le Président, Distingues Invités, Mesdames et Messieurs,

Au nom du sous-ministre associé aux forêts pour la province de Québec, je désire remercier les organisateurs du 10 ième congrès sur les incendies et la météorologie forestière de leur invitation à participer à cette cérémonie d'ouverture. Malheureusement, d'autres activités empêchent monsieur Paillé d'être avec nous ce soir.

En s'associant au congrès comme commanditaire, le ministère de l'énergie et des ressources du Québec veut souligner l'importance qu'il accorde au domaine de la météorologie appliquée à la protection forestière et à la gestion des incendies forestiers.

Le Québec opère un système de protection des forets contre le feu dont le fonctionnement régulier requiert annuellement 28 millions de dollars. À cette somme, s'ajoutent en moyenne 5 millions de dollars pour couvrir les dépenses additionnelles reliées à l'extinction des feux. L'ensemble de ces dépenses se traduisent par une organisation comprenant des effectifs spécialisés, des aéronefs et d'autres équipements qu'on vise à gérer le plus efficacement possible.

La performance du système satisfait pour le moment les responsables gouvernementaux et l'industrie forestière. Il est à prévoir cependant qu'une pression s'exercera dans l'avenir pour améliorer l'efficacité générale de la protection. En effet, le nouveau régime forestier, en vigueur dans la province depuis le premier Avril 1987, impose desormais aux industriels forestiers des responsabilités bien définies dans le domaine de l'aménagement des forêts.

Ces responsabilités devront être assumées dans le respect du principe fondamental de notre nouvelle loi, c'est-à-dire le respect de la possibilité annuelle de coupe a rendement soutenu.

Selon les évaluations actuelles, l'aménagement sur la base du rendement soutenu s'effectuera dans un cadre très serré. Il ne restera que très peu de réserves de bois, une fois que les quelques 275 contrats d'approvisionnement et d'aménagement forestier seront en vigueur au premier Avril 1990.

Il serait inacceptable que des dommages trop élévés, résultant des incendies forestiers, viennent mettre en péril toute la nouvelle orientation.

Comme dans les autres domaines d'activités, l'amélioration de la protection des forêts requiert un effort d'innovation constant. L'évolution rapide de la technologie offre heureusement l'opportunité d'intégrer plus rapidement et plus efficacement les résultats de la recherche et du développement. J'aimerais vous faire part de 3 exemples de ce phénomène qui ont cours au Québec.

D'abord, on s'est interressé de près, au cours des 15 dernières années, à l'amélioration de la quantité et de la qualité de l'information nécessaire à la prise des décisions journalières affectant la détection et le combat des incendies forestiers. Une collaboration assidue, avec l'institut forestier national de Petawawa, a notamment permis de tester avec succès un système moderne d'information de gestion capable de supporter une organisation de protection centralisée opérant dans le sud ouest de la province.

Parmi les informations de base requises par un tel système, il y a bien sur celles touchant les conditions météorologiques. À l'obtention de la meilleure prévision possible du temps, s'ajoute un besoin crucial en protection des forêts: connaître la distrbution de la précipitation dans le territoire. Sur ce point précis, le Québec entend vérifier à fond, avec le concours des organismes compétents en la matière, le potentiel d'un radar météorologique spécialemnent adapté aux besoins particuliers de la protection contre le feu.

D'un autre côté, nous sommes aussi conscients que des améliorations peuvent être apportées à notre système d'évaluation et de prévision du danger de feu. Ainsi, en vue d'intégrer les nouveautés mises au point par les équipes de recherche et par les fournisseurs de produits, nous avons démande aux organismes de protection de la province d'élaborer un plan directeur dont l'objectif est la mise a jour de tous les éléments qui composent notre système de métérologie forestière.

Les trois exemples qui précèdent montrent l'intérêt du Québec à collaborer au développement de la météoriologie appliquée au domaine des incendies forestièrs. Nous desirons par ailleurs profiter des efforts d'amélioration consentis par les autres intervenants dans le domaine. Le congres de cette semaine constitue une bonne occasion d'échanger des idées et de faire du "shopping".

On doit toutefois demeurer conscient que les progrès et les nouvelles techniques ont régulierement des impacts que ce soit sur l'utilisateur individuel ou sur les structures organisationnelles. Pour pouvoir réaliser la meilleur protection au meilleur prix, il faut, de temps a autre, faire le point sur ces considérations. C'est là je crois l'objectif principal de ce congrès.

Le sous-ministre associé aux forêts du Québec me prie de transmettre ses meilleurs voeux de succès aux organisateurs du congrès et aux participants afin que l'objectif soit attenint.

Artificial Intelligence: Where Are We? Whither?

D. LATHAM
Intermountain Fire Science Laboratory
U.S. Forest Service
Missoula, Montana

Abstract

Is Artificial Intelligence a revolutionary approach to computing, an attempt to replicate the human mind in silicon, only another way of doing software engineering; is it salvation or snake oil? Will we all become slaves to our machines or are we developing new ways of interfacing with them? Will all the jobs we now have become obsolete? Will robots roam the forests and rangelands? Robocops police the parks and cities?

Sure. If we don't blow ourselves up or die of starvation. All these things are possible, some in the near term and some in the distant future. Distant to us, that is, but not to a forest...only just tomorrow to a forest.

Predicting the outcome of some of these questions, selecting among the possibilities, is like predicting the outcome of a horse race. There are favourites, but the dark horses can still come from behind and surprise you.

Résumé

L'intelligence artificielle est-elle une approche révolutionnaire à l'informatique, une tentative de reproduction de l'esprit humain en silicone, seulement un autre moyen d'élaborer des logiciels? Sera-t-elle notre salut ou notre perdition? Deviendrons-nous tous des esclaves de nos machines ou sommes-nous à élaborer de nouvelles façons d'interagir avec elles? Tous les emplois que nous occupons maintenant deviendront-ils désuets? Les forêts et les terrains de parcours seront-ils sillonnés par des robots? L'ordre sera-t-il maintenu dans nos parcs et nos villes par des robots?

Bien sûr. Si nous ne faisons pas sauter la planète ou que nous ne mourrons pas de faim. Toutes ces choses sont du domaine du possible, certaines dans un avenir proche, d'autres dans un futur éloigné. Un futur éloigné pour nous, main non pas pour la forêt... le tour de la forêt viendra demain.

Prédire ce qu'il adviendra de certaines de ces questions, retenir certaines possibilités équivaut à prévoir les résultats d'une course de chevaux. Il y a des favoris, mais les montures inconnues peuvent toujours devancer le peloton et nous surprendre.

Lightning Detection Systems: A Status Report

H. NEWHOUSE
National Weather Service
Silver Spring, Maryland

Abstract

The proliferation of lightning detection systems (LDSs) in recent years has led to their growing application in meteorological operations. Primary use has developed in observations and analysis as input to short-term forecasting. The emerging techniques and technology for ground-based LDSs have offered the opportunity for the first time to obtain a comprehensive picture of lightning activity over large areas of the United States. The National Weather Service and other federal agencies have gradually expanded their use of lightning data in recent years. This paper focuses on how lightning data are used today, particularly among government agencies, and the plans agencies have for future applications.

Résumé

La prolifération des systèmes de localisation de la foudre au cours des dernières années a entraîné leur utilisation de plus en plus fréquente en météorologie. Les météorologistes s'en sere principalement dans le cadre d'observations météorologiques et d'analyses comme données d'entrée pour établir les prévisions à court terme. L'avènement de nouvelles techniques et d'une technologie pour des systèmes de localisation de la foudre au sol a permis d'obtenir pour la première fois une image globale de l'activité de la foudre sur de vastes régions des États-Unis. Le National Weather Service et d'autres organismes fédéraux ont graduellement eu de plus en plus recours aux données sur la foudre au cours des dernières années. Le présent article porte sur l'usage actuel des données sur la foudre, notamment par les organismes gouvernementaux et sur les applications futures que prévoient ces organismes.

Introduction

Various federal agencies during the past decade have begun to take advantage of lightning detection systems (LDSs) to meet their operational requirements. Much of this has taken place independently of meteorology, and primarily in response to unique agency needs. The early development of LDSs was mainly in response to the need to protect sensitive operations such as those at airports, rocket launching sites, and nuclear power plants. With time, LDS data began to be applied to gaining a better understanding of mesoscale meteorological processes -- particularly as related to severe storms. The LDS data are also finding growing application by physicists concerned with the earth's electrical budget (global circuit), and observations of lightning from space (Orville and Henderson 1987).

Why Lightning Data

Apart from manual observations by weather observers, pilots, mariners, and others, there is no completely effective way to obtain lightning data. Lightning can be inferred from radar and satellite information, but not in terms of type (cloud-ground, cloud-cloud, and in-cloud), charge (positive or negative), and intensity (amount of current, frequency of strokes, extent of coverage).

The emerging techniques and technology for ground-based LDSs have offered the opportunity for the first time, to obtain a comprehensive picture of lightning activity over large areas of the United States. This in turn has led to growing applications for, and uses of, the data derived from LDSs.

Some of the advantages of LDS data found by forecasters include:

1. Pinpointing convective activity and supporting mesoscale analysis.
2. Discriminating between showers and thunderstorms.
3. Increasing lead time for spotting thunderstorms, and
4. Filling data gaps of other observing systems.

In addition, compared to most other observing systems, LDSs are relatively inexpensive, and the use of lightning data requires comparatively little training.

Lightning Hazards

Although lightning presents a hazard to people in most of the United States, certain areas are much more prone to receive lightning strikes than others due to climatological and topographical factors. The primary area for lightning activity in the United States is contained in a belt along the Gulf Coast extending from Florida to Louisiana (Baldwin 1973). Another major area for lightning includes the Rocky Mountain States -- particularly New Mexico and Colorado.

Certain activities and operations are particularly sensitive to lightning hazards. These include many forms of recreation such as boating and golfing, as well as activities carried on by industry, including aviation operations, power generation and transmission by utility companies, computer operations, construction, and communications.

Uses of Lightning Data

The major uses of lightning data which have emerged during the past decade are:

1. Protection of federal lands including national parks and forests,
2. Protection of power generating plants and transmission networks (Shepard 1986), and more recently,
3. Meteorological applications.

The first two uses of lightning data are based on the idea of early notification of lightning strikes, followed by the rapid deployment of resources to protect property, fight fires, and restore service.

A major cost of maintaining federal lands is connected with fighting forest fires. Studies have shown that getting to the scene of a fire in its early stages will often result in early containment and substantial savings. For this reason, the U.S. Department of Interior's Bureau of Land Management (BLM) has invested in a lightning detection network covering much of the western U.S., where most federal land is located. The BLM has devised its Initial Attack Management System (IAMS), which is designed to rapidly deploy resources to fight forest fires, based on a network of spotters and lightning detectors (OFCM 1985).

Various utility companies have banded together through the Electric Power Research Institute (EPRI) to avail themselves of lightning data -- particularly in the eastern U.S. The data are used to monitor field operations, and to assist in the planning of transmission networks.

The foregoing uses of lightning data have helped pave the way for meteorological applications. Of particular significance in the National Weather Service (NWS) has been the application of lightning data by the NWS Western Region. Weather forecasting in the western United States is hampered by a lack of surface and radar observations. The BLM lightning detection network helps to fill the gap, and has proved to be a valuable tool in the detection of thunderstorms. A variety of lightning products are routinely available to forecasters in the western U.S. Sufficient lightning data has now been collected from some networks so as to provide a basis for developing lightning climatologies and refining thunderstorm probability forecasts, particularly in the west.

Other federal agencies have established their own LDSs to meet their unique requirements. These systems are often for local use as opposed to network configurations. Examples include the USAF/NASA local network at the Kennedy Space Center (KSC) in Florida, and the U.S. Department of Energy local network in Texas associate with a munitions plant.

Many federal agencies have research and development programs underway to delve into further applications of lighting data, as well as to establish a more fundamental understanding of how lightning correlates with other weather phenomena. In some respects, research has lagged behind operational use of the data. The National Severe Storms Laboratory (NSSL) is the leading research agency in the United States with respect to research in storm electricity and mesoscale convective systems.

An effort was also conducted at NSSL to objectively determine how effectively LDSs actually perform. This evaluation was done in central and eastern Oklahoma where lightning detection systems overlap (as shown in Figure 1). One system is manufactured by Lightning

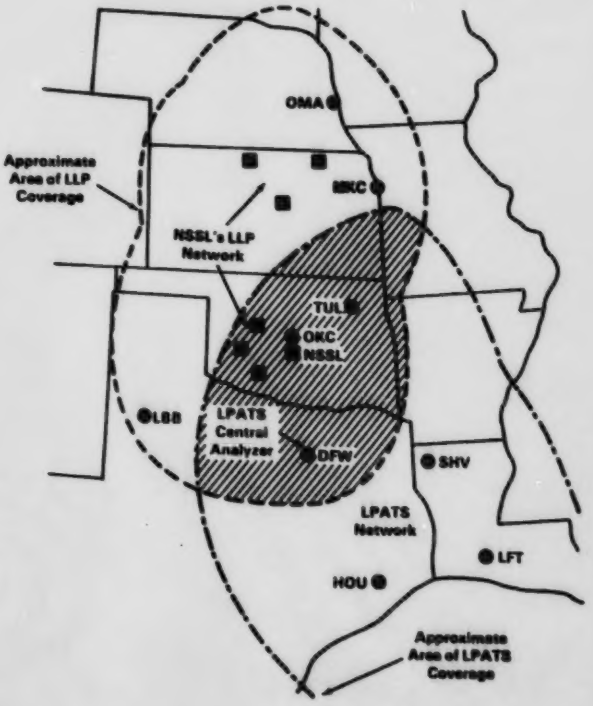


FIG. 1. NSSL instrumented test area.

Location and Protection, Inc., while the other system, referred to as LPATS, is manufactured by Atmospheric Research Systems, Inc. The area of overlap encompasses NSSL facilities including mobile storm-chasing vans equipped with video cameras which are used to obtain ground-truth data on lightning strikes. The laboratory also uses two all-azimuth cameras and an extremely low-frequency radio system to provide reliable identification of ground strikes. This was a two-year effort covering 1986 and 1987 with a final report published in 1988.

Future Plans and Programs

Federal agencies, in addition to pursuing a variety of operational and research interests with respect to lightning data, have banded together to share information and coordinate their activities. This is being done through a newly-formed group under the Office of the Federal Coordinator for Meteorological Services and Supporting Research (OFCM). The group has documented the activities of the respective agencies in the lightning field (OFCM 1987). The group has produced a preliminary national plan for lightning detection systems (OFCM 1988).

Various federal agencies are engaged in operational and research activities with lightning data. Some of these have been noted earlier. Others, such as the National Weather Service, are engaged in a variety of field evaluation programs in order to ascertain how lightning data best fit into forecasting operations. Still others, such as the FAA and AWS are beginning to examine possibilities for applying lightning data to operational and development activities.

While ground-based LDSs have continued to proliferate during the 1980's, another device has emerged as a possibility for the 1990's. This is the lightning mapper (LM), which is under development by NASA. The LM is a sensor designed to detect lightning activity from space. The LM is being considered as a sensor to be flown on a future geostationary satellite (Christian et al. 1984). If the LM is implemented, it is expected to complement ground-based systems by providing coverage of all types of lightning activity over large areas.

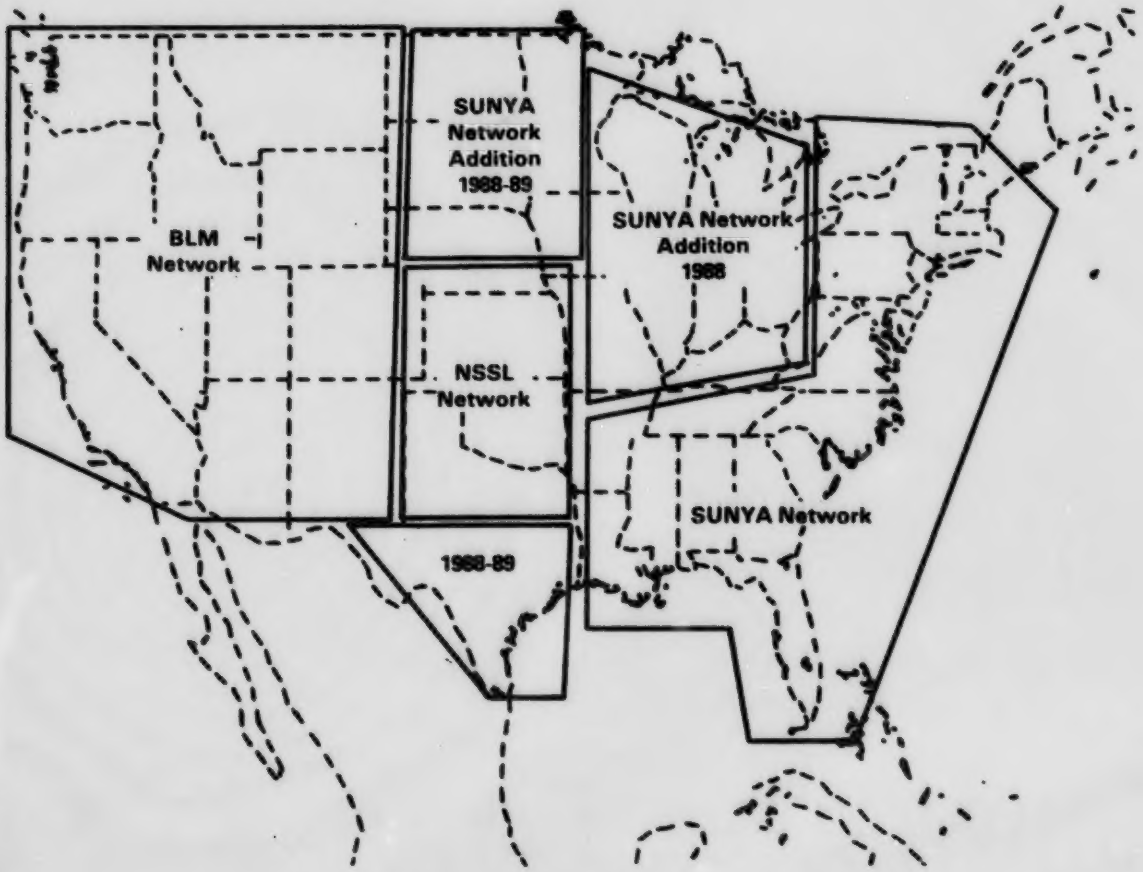


FIG. 2 Experimental national lightning detection network.

Recent Developments

Interest in lightning detection continues to grow. With LDS coverage now available over most of the U.S., a proposal was presented to federal agencies by the State University of New York (SUNY) at Albany to integrate data from regional networks into a national data base (Orville 1987). The proposal for this experimental effort was accepted, and the effort is expected to last 3 years. Agencies will be able to access the data, at their own cost, for evaluation purposes. As in other areas of data exchange, the use of satellite communications is expected to lower costs for individual users. The "building blocks" for the national data base are shown in Figure 2. A national lightning data base offers many possibilities. One example is the development of an experimental graphic product by the NWS summarizing national lightning activity which was recently implemented. Figures 3 and 4 are examples of the graphic product produced.

References

BALDWIN, J.L., 1973. Climates of the Unites States. Washington, United States Department of Commerce.

CHRISTIAN, H.J., W.W. VAUGHAN and J.C. DODGE, 1984. A Technique for the Detection of Lightning from Geostationary Orbit, Preprints of the AMS VII International Conference on Atmospheric Electricity, June 3-8, 1984, Albany, NY.

FEDERAL COORDINATOR FOR METEOROLOGICAL SERVICES AND SUPPORTING RESEARCH, 1985. Lightning Detection Study, FCM-R8-1985, 41 pp.

FEDERAL COORDINATOR FOR METEOROLOGICAL SERVICES AND SUPPORTING RESEARCH, 1987. The Status of National Programs for Lightning Detection Systems, Revised by OFCM 2-6-87, 50 pp.

FEDERAL COORDINATOR FOR METEOROLOGICAL SERVICES AND SUPPORTING RESEARCH, 1988. Preliminary National Plan for Lightning Detection Systems, FCM-P22-1988, 45 pp.

ORVILLE, R.E. and R.W. HENDERSON, 1987. Global Distribution of Midnight Lightning: September 1977 to August 1978. Monthly Weather Review, 114:12:2640-2653.

ORVILLE, R.E., 1987. A National Lightning Detection Network. Unpublished proposal, State University of New York, Albany.

SHEPARD, M., 1986. Getting a Fix on Lighting Strikes, EPRI Journal, November 1986, 24-29.

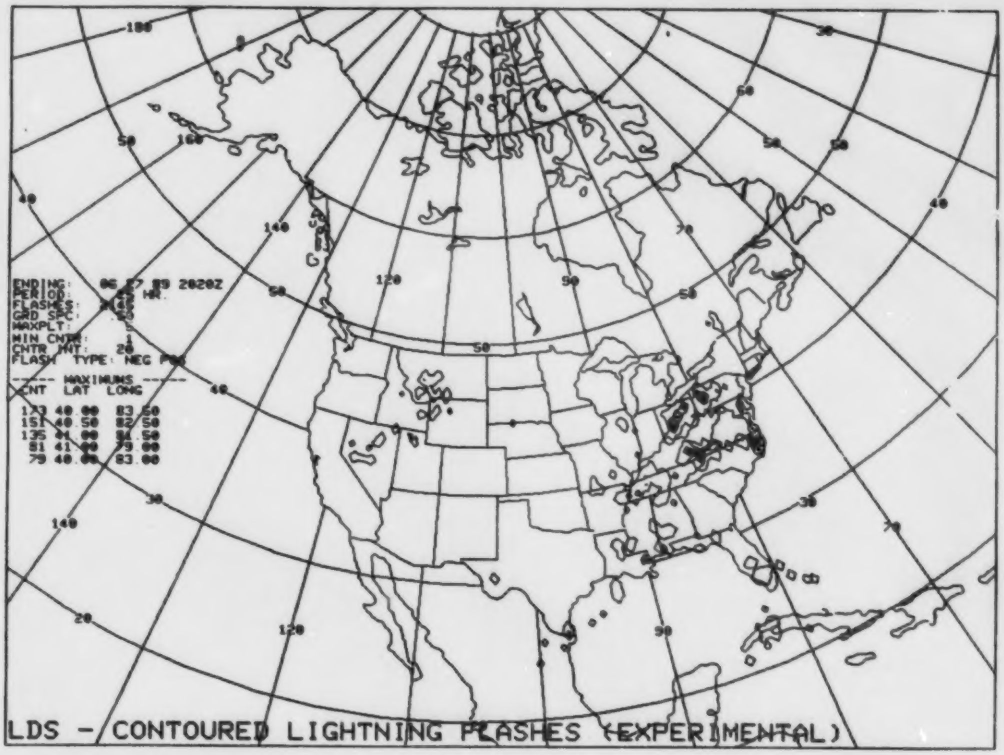

ENDING: 06 27 89 2020Z
PERIOD: HR.
FLASHES:
GRD SPC: 50
MAXPLT: 5
MIN CNTR: 1
CNTR INT: 20
FLASH TYPE: NEG POS
----- MAXIMUMS -----
CNT LAT LONG
173 40.00 83.50
151 40.50 82.50
135 41.00 81.50
81 41.00 79.00
79 40.00 83.00
180
160
140
120
90
70
60
50
40
30
20
LDS - CONTOURED LIGHTNING FLASHES (EXPERIMENTAL)

FIG. 3

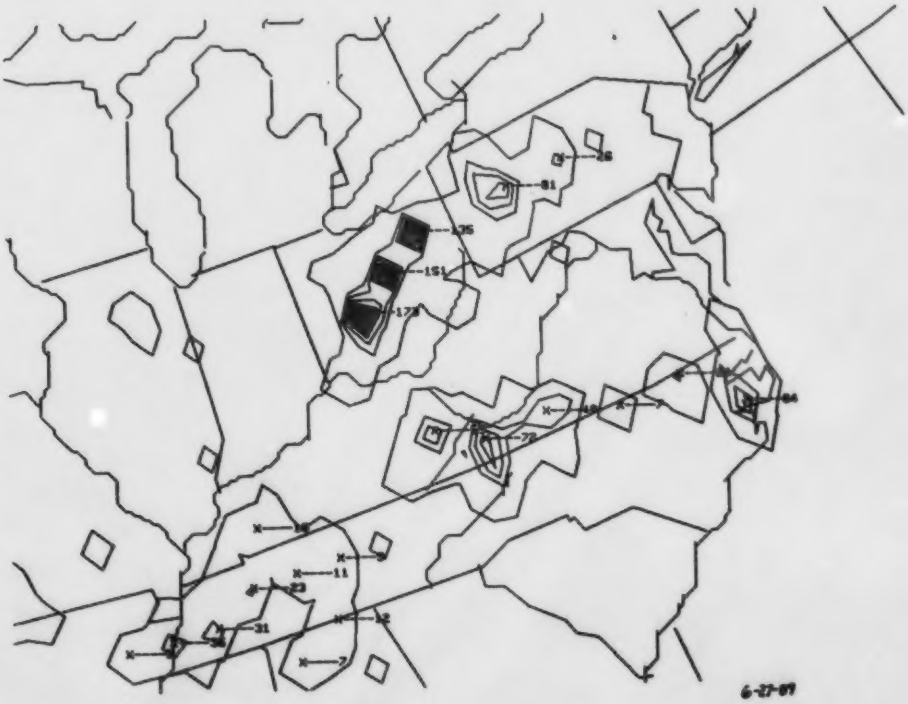

26
81
135
151
173
72
7
64
16
9
11
23
31
12
36
7
6-27-89

FIG. 4

Ground-Truthing of LLP Lightning Location Data in Alberta

N. NIMCHUK
Alberta Forest Service
Edmonton, Alberta

Abstract

The Forest Protection Branch of the Alberta Forest Service operates an extensive manned fire lookout network and an electronic lightning detection system. This coincident operation has provided the data to monitor and verify the performance of the lightning detection system during the fire season. Since 1985, 350 incidents of lightning striking lookout structures have been documented by lookout personnel throughout Alberta. These incidents are used for ground truthing of the lightning detection system's location accuracy and to assess the detection efficiency of the system. Performance characteristics of individual direction finders are also examined.

Résumé

La direction de la protection contre les incendies au service forestier de l'Alberta opère un réseau manuel de surveillance contre les incendies et un système électronique de détection de la foudre. Cette opération coincidente a fournie les données nécessaires pour surveiller et vérifier la performance du système de détection de la foudre pendant la saison des incendies. Depuis 1985, le personnel de surveillance à travers l'Alberta a documenté 350 incendents ou la foudre avait frappée les structures de surveillance. On se sert de ces incidents comme référence-zerrain de l'exactitude de l'emplacement du système de détection de la foudre et pour évaluer l'éfficacité de détection du système. Les caractéristiques de performance des viseurs individuels de direction sont aussi examinées.

Introduction

During the past 10 years there has been an extensive deployment of electronic lightning detection systems throughout much of North America. Most of the operational systems have been manufactured by Lightning Location and Protection, Inc., (LLP) (Krider et al. 1980). The majority of these systems are operated by fire management agencies. Automated lightning detection has significantly enhanced the capability of fire managers to detect and suppress lightning-caused wildfires.

The mandate of the Alberta Forest Service Protection Branch requires the suppression of all wildfires. Early fire detection and rapid initial attack are the key elements of Alberta's suppression program. In order to help meet these objectives, the Alberta Forest Service introduced an LLP-type lightning detection system in 1983. The emphasis on rapid initial attack in Alberta has produced a keen awareness of lightning fire danger among fire managers. Consequently, the LLP data have been closely observed and scrutinized.

Initially fire managers held very high expectations about the lightning detection system's location accuracy and detection efficiency. Specifications provided by the manufacturer in 1983 indicated location errors of 1-3 km and a detection efficiency of 80 to 90% (Krider et al. 1980). These performance figures were based on LLP's experience with relatively short baseline systems. With the significantly longer baselines of the Alberta system, it became apparent that somewhat larger than expected errors were present in the lightning data. These errors were being detected in the field by comparing the visual lightning observations at manned lookouts with the lightning locations depicted on the forest headquarter display units. Several fire managers observed that errors of 5-10 km were fairly consistent in their local jurisdiction and made allowance for them in fire operations. Others found the errors to be more random in nature with location errors of 20-30 km or more and only a small fraction of the apparent activity detected by the system.

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

Fire managers in areas with low detection efficiency and large location errors were understandably disappointed and voiced a lack of confidence in the entire automated lightning detection system. These concerns prompted the verification and ground-truthing project described in this paper. The manned lookout network consists of about 140 lookout towers. A comparison of the LLP generated data and the "direct hit" data permits a definitive ground truthing and verification. This verification project is unique in that it uses numerous fixed observation sites to ground-truth the automated data.

This paper summarizes the verification results obtained during the 1985-88 lightning seasons. In addition to providing quantitative assessments of location error and detection efficiency, azimuth or bearing errors of individual direction finder (DF) sites are also analysed. The bearing errors generate a more complete picture of DF characteristics and thereby aid in the identification of site or alignment problems.

The Alberta Lightning Detection System

The Alberta Forest Service introduced a stand-alone LLP-type lightning DF site in 1979. An integrated network consisting of a position analyser (PA), seven DFs and ten remote display processors (RDP), was established in 1983. By 1985 three out-of-province DF sites were added to the network. Co-operative agreements with government and private agencies led to the expansion of the network through 1988 to include 14 DF sites and 14 RDP's (Fig. 1). All lightning location data are accessed in real time throughout the network. Alberta fire managers would strongly resist any restriction of their real time lightning data access.

The Alberta Manned Lookout Network

The manned lookout has been the frontline for fire detection in Alberta for nearly 50 years. This extensive fixed detection network had 143 lookout stations in 1988 (Fig. 2). The typical lookout person has an experience level of five to ten fire seasons. With few exceptions they are astute and reliable observers.

The primary tasks of the lookout include:

1. Detection and surveillance of wildfires.
2. Performing detailed weather observations twice daily including the observation and monitoring of convective cloud and lightning activity.
3. Providing a forestry communications link in the remote regions of the province.

Since lookouts are intended to visually survey large areas, they are normally situated on high ground. In the non-mountainous forest areas lookouts are generally of the classic metallic tower type and range from 20 to 30 m in height. The tower's fibreglass cupola is generally situated several metres above the surrounding forest canopy. Mountain lookouts along the east slopes of the Rockies are basically wooden cabin-like structures built on significant peaks. Overall, the basic construction and environment of lookouts enhance their risk of being struck by lightning. Proper grounding of lookout facilities receives particular attention. Although there have been numerous "direct hits", there have not been any incidents of the lookout structures catching fire or the lookout person being seriously injured.

Data Collection

Beginning in 1985, lookouts have routinely documented two types of lightning events:

1. "Near miss" - any observed cloud-to-ground lightning in the vicinity of the lookout where the

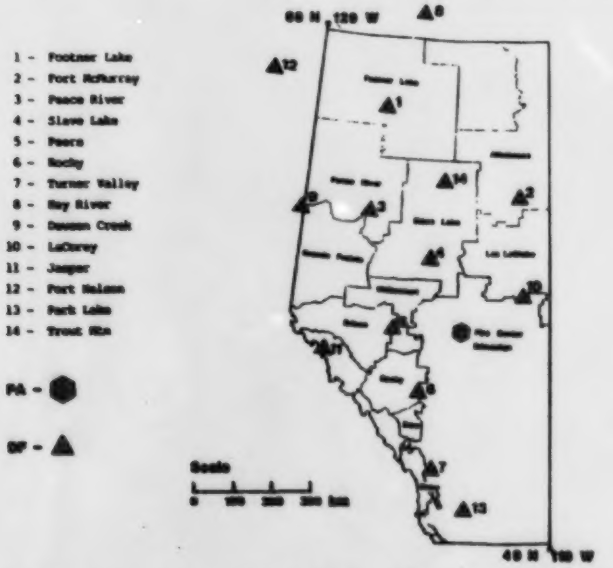


FIG 1. Alberta LLP system PA and DF locations and forest region boundaries.

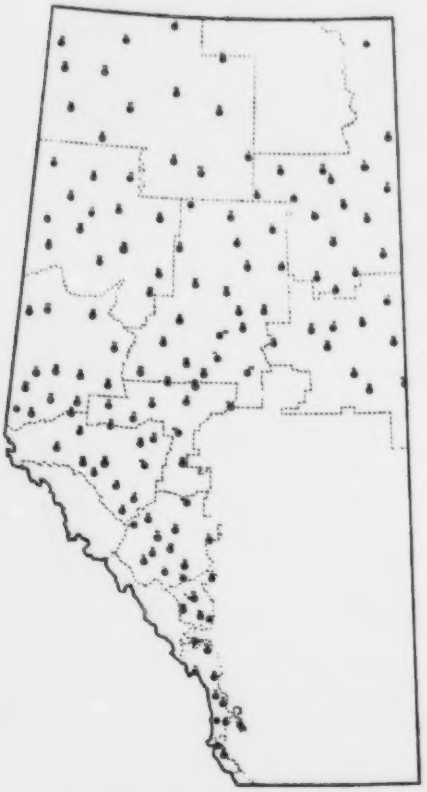


FIG 2. Locations of the primary manned lookout stations in Alberta.

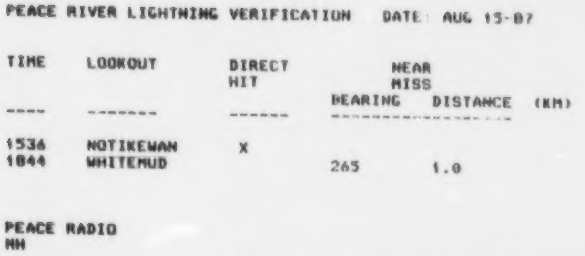
interval between the flash and resulting thunder was three seconds or less.

2. "Direct hit" - lightning directly strikes the lookout or its related structure.

Documentation of the events includes:

1. Lookout identifier.
2. Time - recorded to the nearest minute.
3. Type - near miss or direct hit. If possible, in near miss cases an approximate bearing to the flash is also included.

As soon as possible after the event, the data are transmitted by voice communication to forest head quarters and relayed by teletype to the Fire Center in Edmonton. Examples of a direct hit lightning event report and associated display map are given in Figures 3 and 4. Data collection in this operational environment is potentially subject to errors. Possible significant errors include false identification of the lightning event and inaccurate time records of events.



```
PEACE RIVER LIGHTNING VERIFICATION   DATE: AUG 15-87

TIME   LOOKOUT     DIRECT         NEAR
                   HIT            MISS
                           BEARING   DISTANCE  (KM)
----   -------     ------  ------------------

1536   NOTIKEWAN     X
1844   WHITEMUD            265       1.0


PEACE RADIO
MH
```

FIG 3. Example of a lightning verification report from Peace River Forest lookouts Notikewan (NO) and Whitemud (WD).

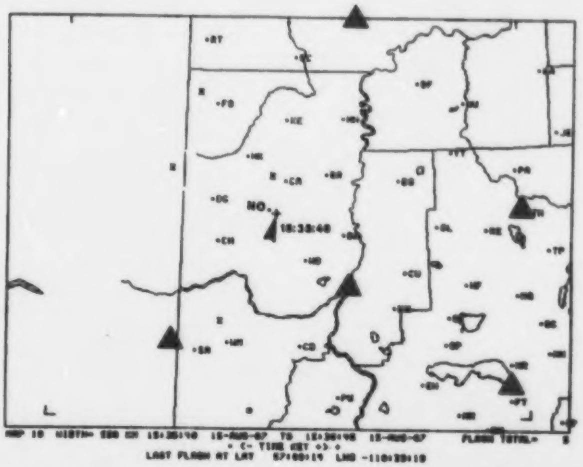


FIG 4. Lightning display map for the period 1530 to 1540 MDT August 15, 1987. Location and PA recorded time of positive lightning flash directly striking Notikewan tower as reported in Fig. 3 is shown (arrow).

Several factors tend to minimize these errors. The generally high experience level and weather awareness of lookout personnel considerably reduce the possibility of false reports. With respect to the timing of observed lightning events, lookouts are required to adhere to regular radio broadcast schedules co-ordinated through forest headquarters. Consequently, consistent and accurate timekeeping is maintained at lookout stations. The PA clock in Edmonton is routinely checked against the universal co-ordinated time signal.

Some variance in the lightning event time record is expected between the lookout and the PA. A difference of five minutes between records was considered to be excessive in the study and would place the event in the undetected category. This situation occurred in less than 10 documented direct hits. Correlation of the lookout report and the lightning display data is a relatively straightforward procedure with the RDP. The RDP allows replay of stored data at greatly reduced speeds. As all lookouts are depicted on the RDP map base (see Fig. 4) by location and two letter identifier, individual flashes affecting a specific lookout at a specific time can be isolated. In most cases such a lightning flash is an isolated event and is readily identified. Given the PA time of the event, the data for the individual flash can then be retrieved from the tape archive.

Data Analysis

The "direct hit" lightning event is best suited for quantitatively assessing location and bearing errors since the geographical co-ordinates of the lookout sites are precisely known. For this reason only "direct hits" are considered in this study.

Over the past four fire seasons a total of 350 direct hits have been documented and analysed. The latitude and longitude co-ordinates in decimal degrees of the lookout site, lightning flash and DF site provide the necessary inputs to the standard geodetic equations (Bomford 1980, Pg. 120-121). From the equations we obtain:

1. Flash location error - the distance between the lookout site and the display lightning location (see Fig. 4 for example).
2. Bearing and distance from the DF sites which detected the direct hit to the lookout (see Fig. 4 for example).

The bearing error is defined as the difference between the bearing recorded by the DF and the bearing calculated from the DF to the lookout. In addition to the calculation of location and DF bearing errors, the polarity, estimated peak current and multiplicity of the direct hit lightning flash are also documented.

Results and Discussion

LOCATION ERRORS

The yearly statistics of detection performance and mean location error are summarized in Table 1. The data for the entire network from Table 1 indicate an increase in mean location error after 1985 from approximately 7-11 km. These consistently higher errors during 1986-88 can be partly attributed to larger sample sizes and inclusion of data from the periphery of the network that is prone to baseline calculations and low DF densities. A more complete forest-by-forest picture of the location errors is provided by Table 2.

Table 1. Yearly direct hit statistics and mean values of detection performance and location error: 1985-88.

Year	Direct hits	Undetected	Performance Detection (%)	Mean Location error (km)
1985	54	16	70	7.2
1986	75	14	81	10.0
1987	142	32	77	11.0
1988	79	18	77	11.7
Total	350	79	76	9.8

Table 2. Mean location errors and number of direct hits by year and forest: 1985-88.

	Year Mean location error (km) and (total direct hits)			
Forest	1985	1986	1987	1988
Footner Lake	--	--	17.8 (3)	12.5 (5)
Peace River	8.6 (1)	11.0 (5)	9.2 (7)	12.9 (5)
Grande Prairie	10.9 (6)	15.2 (3)	17.1 (10)	14.3 (5)
Slave Lake	3.7 (11)	11.1 (12)	8.0 (13)	11.7 (7)
Athabasca	19.8 (2)	31.1 (1)	18.8 (12)	22.3 (4)
Lac La Biche	12.8 (2)	11.8 (2)	8.5 (1)	--
Whitecourt	16.4 (1)	10.6 (10)	10.4 (26)	9.9 (4)
Edson	--	--	9.3 (9)	11.9 (9)
Rocky	3.6 (12)	7.0 (12)	3.4 (3)	9.3 (12)
Bow/Crow	4.5 (3)	7.9 (16)	4.4 (26)	8.8 (11)

The forest-by-forest data indicate a strong positive correlation between location error and DF density. The Whitecourt, Edson, Rocky and Bow/Crow Forests are situated within the highest DF density area of the lightning network with a mean DF baseline distance of approximately 230 km. These forests combined have a mean location error of 9.9 km. Conversely, the northern forests of Footner Lake and Athabasca are subject to a lower DF density with a mean baseline distance of 325 km and subsequently higher mean location errors of 17.4 km. A good deal of variability is exhibited by the data (e.g., Rocky). In addition to varying sample sizes and peripheral data, changes in system and DF site configuration during 1985-88 likely contributed to this variability as well. The distribution of lightning location errors is further illustrated in the discussion of the comparison of the verification data with an optimized error model.

DETECTION EFFICIENCY

The detection efficiency is the most difficult performance characteristic of the lightning system to assess with precision. The total amount of lightning occurring in any storm event is an indeterminate figure. Therefore most efficiency studies in the literature have approached the problem by statistically comparing the amount of lightning detected by individual DF stations within a network. This process yields a relative "detection efficiency" for each DF and has proven useful in identifying DF sites with weak detection characteristics (Gilbert et al. 1987, Droog 1987).

As noted in Table 1, the Alberta verification data showed that 271 of 350, or 76%, of the direct hit events were detected by the network. As in the case of the location error data, a more complete picture of detection performance is obtained by examining the detection statistics on a forest-by-forest basis (Table 3).

The detection data from Table 3 illustrate two significant features:

1. A large proportion (35%) of the documented events occurred in the mountainous Rocky and Bow/Crow Forests. Only 10% of the events were recorded in the northern forest regions of Footner Lake and Athabasca.
2. Considering those years which had at least 10 direct hit events in the forest, the highest detection performances occurred in high DF density forests of southern Slave Lake, Whitecourt, Rocky and Bow/Crow.

Although it is invalid to calculate a definitive "detection efficiency" for the network on the basis of the verification data, the analysis does provide an indication of where the network's detection performance is relatively weak. This may then lead to further investigation of DF sites or the network configuration in the area.

IDENTIFICATION OF A DF SITE PROBLEM

A significant increase in mean location error was observed in the 1986-88 Slave Lake Forest verification data (Table 2). This was of particular interest since the Slave Lake DF antennas had been lowered from a detached tower to the top of the shelter. The verification data raised concern that the relocation of the sensing antenna adversely influenced the DF site's performance.

However, examination of the Slave Lake DF bearing errors (Figs. 5-8) revealed evidence of a serious site problem that was likely unrelated to the antenna relocation.

The Slave Lake DF is situated at mid-slope on the northwest aspect of a 300 m forested hill. The slope gradient to the site is approximately 8%. Consequently, waveforms must traverse a sharp topographical discontinuity in the immediate vicinity of the sensing antennas. The 1987-88 bearing error data (Figs. 7 and 8) provide evidence of a particularly strong distortion in the lightning waveforms within the 180 to 270 degree quadrant. Significant errors also appear in the other available data. The lower mean location error in Slave Lake Forest in 1985 (Table 2) was the result of verification data obtained at lookouts that were located within a 60 km radius of the Slave Lake DF. The close proximity of the events tended to reduce the influence of large bearing errors. Data from 1987-88 included several direct hits at lookouts 100-250 km from the Slave Lake DF and more clearly reflect the bearing errors at the site.[1]

COMPARISON OF VERIFICATION DATA VS. AN OPTIMIZED ERROR MODEL

Generally the bearing error data indicate that absolute errors of two to four degrees are typical at Alberta DF sites that are considered "clean" electronically. Although a one degree random error is specified for the equipment, larger errors due to propagation effects

Table 3. Direct hits detected and undetected by year and forest: 1985-88

D = detected U = undetected R = D/(D+U)

	1985			1986			1987			1988		
FOREST	D	U	R (%)	D	U	R (%)	D	U	R (%)	D	U	R (%)
Footner Lake	-	-	-	-	-	-	3	5	38	5	0	100
Peace River	1	1	50	5	2	71	7	1	88	4	2	67
Grande Praire	6	3	67	3	1	75	10	2	82	5	3	63
Slave Lake	11	0	100	12	2	86	13	2	87	7	1	88
Athabasca	2	5	78	1	0	100	12	0	100	6	3	67
Lac La Biche	2	1	67	2	1	67	1	0	100	1	0	100
Whitecourt	1	0	100	10	1	91	21	2	91	3	4	42
Edson	-	-	-	-	-	-	9	10	47	9	4	69
Rocky	12	1	92	12	2	86	3	1	75	10	0	100
Bow/Crow	4	4	50	16	5	76	29	11	73	10	2	83

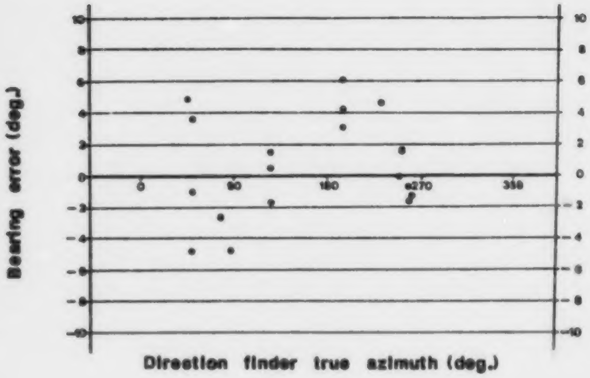


FIG 5. Bearing errors at Slave Lake DF site - 1985.

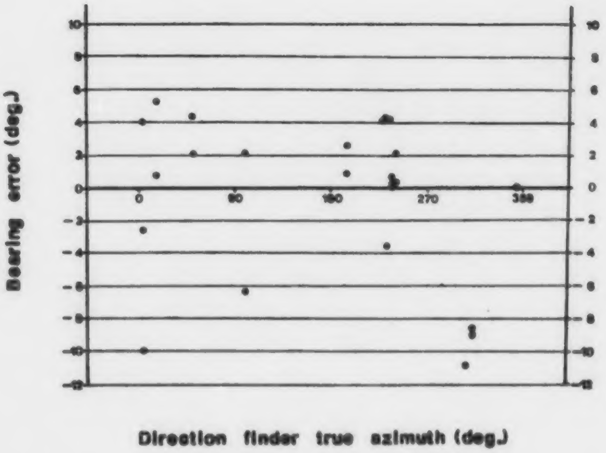


FIG 6. Bearing errors at Slave Lake DF site - 1986.

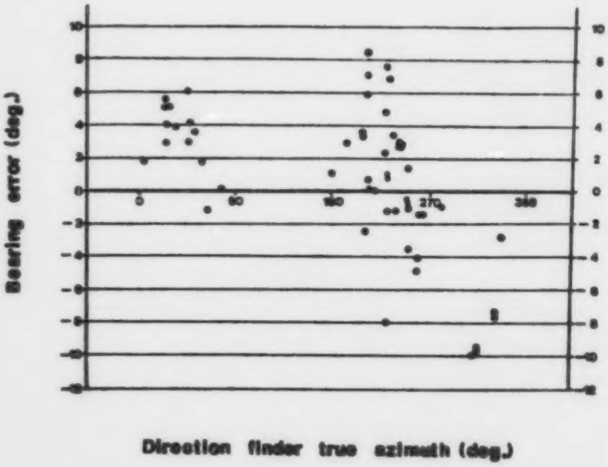


FIG 7. Bearing errors at Slave Lake DF site - 1987.

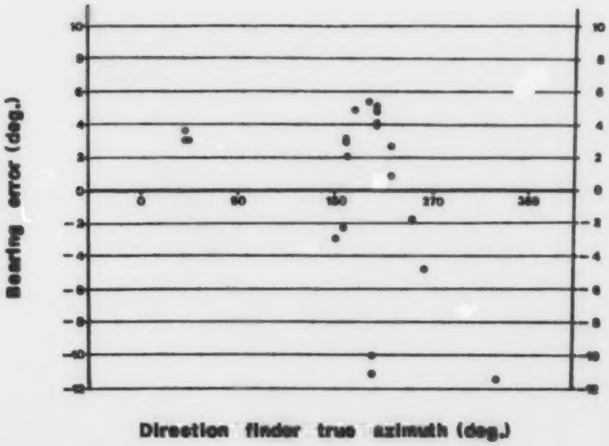


FIG 8. Bearing errors at Slave Lake DF site - 1988.

in the operational environment should be expected. Site problems induce additional errors - a serious site problem at a single strategically located DF adversely affects system performance over a large area. Comparison of the mean location error data (Fig. 9) with an optimized error model provided by LLP (Fig. 10) indicates that the Alberta LLP system's location accuracy has been negatively influenced by large site induced bearing errors at the Slave Lake DF.

The optimized model assumes no propagation or site errors, a random bearing error of one degree at all DF sites and utilizes the standard PA algorithm. Despite these assumptions, the accuracy estimate provides a general basis for comparison and should aid in the identification of system problems. From the model, central Alberta should expect an optimum location accuracy of 4-8 km. The verification data show substantially higher errors of 10-14 km particularly within a 200 km radius of the Slave Lake DF. Better agreement is found in areas beyond the effective range of the Slave Lake DF; the Rocky and Bow/Crow Forests display general agreement with the error model. Higher location errors in the northern areas of the province due to a lower DF density are clearly indicated by the model and the verification data.

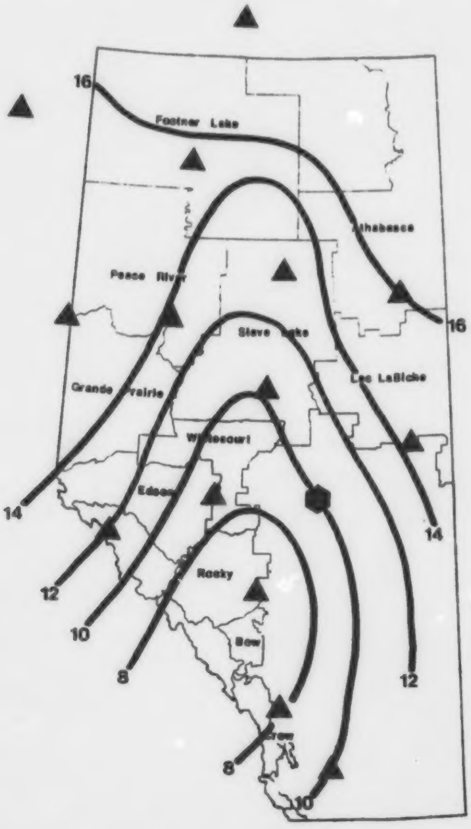


FIG 9. Mean location error (km): 1985-1988.

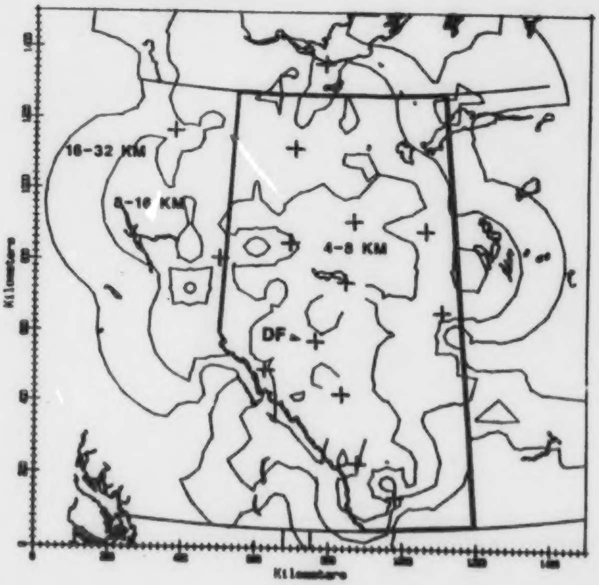


FIG 10. Estimated Alberta LLP system location error (Hiscox 1989).

Conclusion

The ability to ground truth LLP lightning data provides the fire manager with a reliable assessment of lightning detection system performance. The study has largely restored confidence in the lightning detection system among previously skeptical Alberta fire managers. It has accomplished this by confirming many aspects of their own experience with the system in the field and by providing a more complete explanation of system performance characteristics. From a technical perspective, ground truthing greatly aids in the diagnosis of deficiencies in system coverage, electronic or antenna alignment errors and site problems. In Alberta, this capability has played a crucial role in the management of the lightning detection network. The verification data have led directly to the relocation of problem DF sites and the identification of areas of inadequate system coverage. Ground truthing of the lightning data allows a degree of quality control to be exercised over the system and contributes markedly towards maintaining the highest possible level of performance.

Acknowledgements

The author wishes to thank B. Janz, Fire Weather Supervisor, Alberta Forest Service and B. Hiscox of LLP, Inc. for their helpful suggestions. J. Hunka, Electronics Technician, Alberta Forest Service, supplied valuable technical support. J. Laviolette thoughtfully reviewed the manuscript. N. Shulhan patiently typed the manuscript.

Endnotes

[1] Direct hits at distances greater than 350 km from any DF are not utilized in bearing error analysis

References

BOMFORD, G. 1980. GEODESY. 4th ed. Oxford University Press.

DROOG, W. 1987. A method for assessing direction finder site detection efficiency and the results from the 1986 OMNR network assessment. Ontario Ministry of Natural Resources. AFMC #239.

GILBERT, D., B. JOHNSON, and C. ZALA. 1987. A reliability study of the lightning locating network in British Columbia. Can. J. For. Res. 17: 1060-1065.

KRIDER, E.P., R.C. NOGGLE, A.E. PIFER, and D.L. VANCE. 1980. Lightning direction-finding systems for forest fire detection. Bul. Amer. Met. Soc. Vol. 61, No. 9: 980-986.

MCGORMAN, D.R., and W.D. RUST. 1988. An evaluation of two lightning ground strike locating systems. NOAA, nvironmental Research Lab., NSSL.

MACK, D.M. 1984. Evaluation of an LLP ground strike locating system. Unpublished MSc thesis. Engineering physics. University of Oklahoma. 54 p.

NIMCHUK, N. 1986. Verification of lightning location data. Unpublished manuscript. Presented at Lightning Det. Workshop, LLP Inc., Jan. 28 - 31, 1986, Tucson, Az.

Spatially Integrated Radiation Under Lodgepole Pine Canopies

D.F. POTTS
University of Montana
Missoula, Montana

R.D. HUNGERFORD
Intermountain Fire Sci. Lab.
Missoula, Montana

Abstract

The radiation regime under forest canopies exhibits tremendous spatial and temporal variability. Despite considerable work towards characterizing this environment, a great deal remains to be learned about the controls over that variability, and we still lack reliable predictors based on commonly measured stand parameters. Objectives of this study were to: 1) characterize the shortwave, net and photosynthetically active radiation environments under four lodgepole pine canopy densities using mobile sensors; and 2) develop predictive relationships between transmissivity and common mensurational parameters.

A set of radiometers and a data logger were used to record radiation data in a large clearcut in west-central Montana. Simultaneously, in an adjacent 50 year-old lodgepole pine stand thinned to 4 nominal basal area treatments, a duplicate set of radiometers and data logger, mounted on a two-wheeled cart, were moved at a rate of about 2 meters per minute along fixed transects beneath the canopy. Measurements were usually completed within a two hour period around solar noon. Data were obtained on 9 days (ranging from clear to partly cloudy), beginning in July and ending in November, to provide a range of solar angles.

Resulting empirical canopy transmissivity equations, canopy radiation extinction coefficients, and an analysis of their sun angle dependence are presented and discussed.

Résumé

Le régime de rayonnement sous des couverts forestiers présente une énorme variabilité spatiale et temporelle. Malgré les efforts considérables déployés pour caractériser cet environnement, il reste beaucoup à apprendre sur les facteurs contrôlant cette variabilité et nous ne disposons toujours pas de prédicteurs fiables basés sur des paramètres des peuplements couramment mesurés. La présente étude avait pour objectifs: 1) de caractériser à l'aide de capteurs mobiles les environnements de rayonnement de courte longueur d'onde, de rayonnement net et de rayonnement photosynthétique ment óctif, utilisable sous des couverts de pins tordus de quatre densités différentes; et 2) d'élaborer des relations prévisionnelles entre la transmississivité et les paramètres couramment mesurés.

Une série de radiomètres et un enregistreur de données ont servi à enregistrer des données sur le rayonnement dans un grand parterre de coupe rase du centre-ouest du Montana. L'expérience était répétée simultanément dans un peuplement adjacent de pins tordus de 50 ans éclairci en fonction de 4 traitements aux surfaces terrières nominales, une série en duplicata de radiomètres et un enregistreur de données montés sur un véhicule à deux roues le parcourant à une vitesse d'environ 2 mètres par minute le long de transects pré-établis sous le couvert. Les mesures étaient généralement toute prises en moins de deux heures, vers midi, à l'heure du soleil. Les données ont été recueillies pendant 9 jours (le temps allant de clair à partiellement nuageux) du début de juillet à la fin de novembre pour obtenir une gamme d'angles différents du soleil. Les équations sur la transmissivité empirique du couvert ainsi obtenues, des coefficients d'atténuation du rayonnement par le couvert et une analyse de la dépendance à l'égard de l'angle du soleil sont présentés et examinés.

Introduction

A brief presentation of rationale and objectives for this study appears in the Abstract, and will not be repeated here. There has been considerable recent literature, representing various disciplines, on development and application of Beer-Lambert Law canopy radiation attenuation models employing allometric relationships to determine canopy structure (e.g. Pierce and Running 1988). The Beer-Lambert Law assumes that canopy transmittance (T) is exponentially related to canopy structure by the functional relationship:

$$T = \exp(-K * LAI) \tag{1}$$

where K is an extinction coefficient and LAI is the projected Leaf Area Index. Canopy transmittance, T, is usally expressed as the ratio of radiation measured at some level in or below the canopy to the energy flux density measured above the canopy.

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

Methods

SITE

The 3.85 ha, 60 year-old lodgepole pine stand used in this study is located on Lubrecht Experimental Forest in west-central Montana at approximately 47 longitude degrees N. latitude and 1250 m elevation. A portion of the stand was clear cut, the remainder thinned to nominal densities of 270, 545, 1090, and 1750 stems/ha corresponding to stand basal areas of about 12, 18, 20 and 31 m^2/ha respectively. Projected leaf area indices for these treaments were estimated with the basal area/LAI allometric relationship developed by Hungerford (1987) and had values of 0.9, 1.4, 1.6, and 2.4, respectively.

MEASUREMENTS

PAR, net and shortwave radiation were sampled with a mobile sensor system on fixed transects beneath the canopy and at the same time with a duplicate instrument set in the adjacent clearcut on 9 sunny to partly cloudy days during summer and fall of 1987. Solar elevation angles ranged from 27 to 65 degrees. The mobile sensors were moved at a rate of about 2 meters per minute to allow response to sunflecks.

Results and Discussion

Only the results of the shortwave radiation investigation are presented here. Results for the other 2 radiation components are similar with only slight differences in calculated extinction coefficients. To simplify the analyses, transmission data were averaged in 3 solar elevation "classes" determined by the approximate solar elevation angle at the actual time of measurement. The average angle for these classes are 60, 45 and 36 degrees, respectively.

The results of 2 individual data runs through the 20 m^2/ha treatment at high and low sun angles are shown in Figure 1. The time intervals correspond to the same distances along the transect of about 38 m. Note the considerable transmissivity variation in space and time. Transmission values were averaged in treatments and sun angle classes for subsequent analysis.

Figure 2 shows the average shortwave transmission by treatment and sun angle class. Both figures indicate considerable angle dependence on canopy transmission, but it is unclear whether this is due to changing extinction coefficients or to penetration of more biomass at lower sun angles.

Figure 3 shows how a simple projected LAI becomes a much higher "effective" LAI at lower sun angles. Extinction coefficients calculated by eqn. 1, using projected LAI for the 12 combinations of basal area and sun angle, ranged from .62 to 1.3 and averaged .94. Extinction coefficients calculated using effective LAI averaged .65 with a standard deviation of only .09. Not only is this very close to the average reported for conifer canopies (Pierce and Running 1988), but the small range indicates very little solar angle dependence.

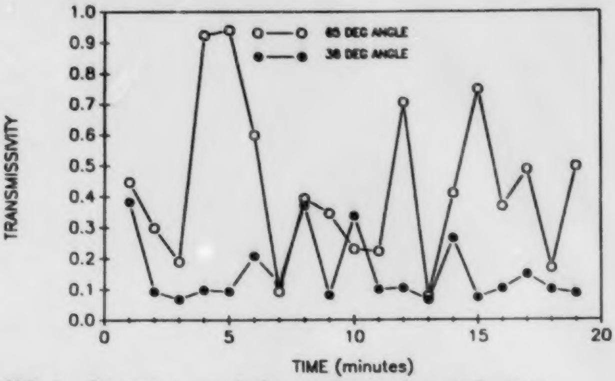


FIG 1. Canopy transmission varies in time and space.

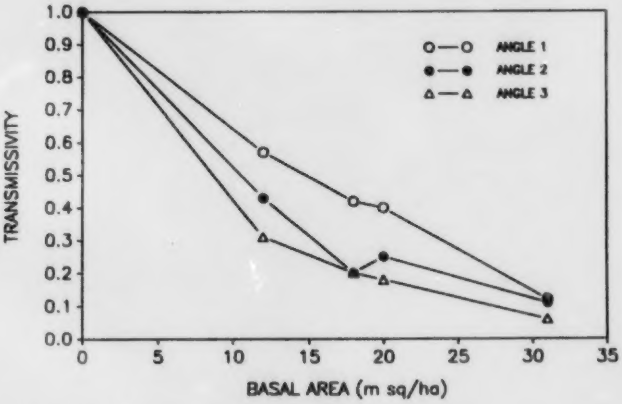


FIG 2. The effect of basal area and sun angle.

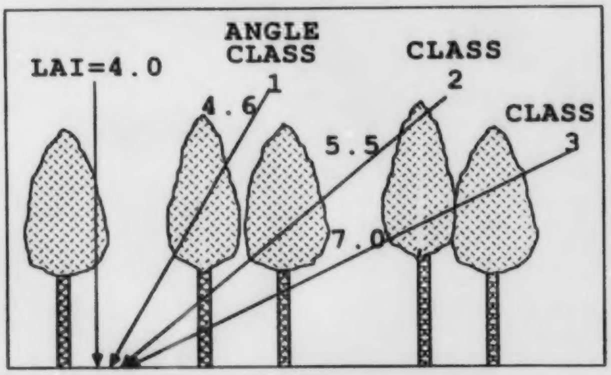


FIG 3. Sun angle and effective leaf area index.

References

HUNGERFORD, R.D. 1987. Estimation of foliage area in dense Montana lodgepole pine stands. Can. J. For. Res. 17:320-324.

PIERCE, L.L. AND S.W. RUNNING. 1988. Rapid estimation of coniferous forest leaf area index using a portable integrating radiometer. Ecology 69(6): 1762-1767

Aerodynamic Parameters of a Mature Mixed Forest, Chalk River, Ontario

D. BRANSON
Queen's University
Department of Geography
Kingston, Ontario

Abstract

Application of the Penman-Monteith model for estimating forest evaporation requires an understanding of aerodynamic and surface resistance behaviour of the vegetative cover. Wind profile data collected during the summer of 1987 at Petawawa National Forestry Institute (PNFI), was used to determine zero plane displacement (d), roughness length (z_0) and friction velocity (u_*) for 368 near-neutral profiles ($-0.05 \leq Ri \leq 0.05$). Zero plane displacements were determined using both the mass conservation and least squares methods. Results from the mass conservation method were viewed as more reliable and displayed dependence of d and z_0 on wind speed: d decreased and z_0 increased with increasing wind velocity. Using this method the mean d was found to be 13.43 ± 1.16 m (or d/h=0.67, where h is canopy height) and z_0 was 2.72 ± 0.87 m (or $z_0/h=0.14$).

Aerodynamic resistances for momentum r_{aM} were determined using wind speed dependent relationships for d and z_0. These were compared to those determined using constant profile parameters often quoted for agricultural crops, d/h=0.63 and $z_0/h=0.13$ (Monteith 1973), and for forest d/h=0.76 and $z_0/h=0.075$ (Jarvis et al. 1976). The incremental resistance (r_b) was calculated using the approximation $r_b=4/u_*$, and included in the equation for aerodynamic resistance to water vapour r_{aV}. The values of r_{aV}, along with independent Bowen ratio/energy balance measurements of evaporation, will be used to determine surface resistance r_c from the Penman-Monteith model.

Résumé

Pour l'application du modèle Penman-Monteith conçu pour estimer l'évaporation en forêt, il faut comprendre le comportement de la résistance aérodynamique et superficielle de la couverture négétale. Les données du profil du vent recueillies pendant lété 1987, a l'institut national forestier de Petawawa (INFP) ont servi à déterminer le déplacement nul du plan (d), la longueur de rugosité (z_o) et la vitesse de frottement (u_*) pour 368 profils neutres ($-0,05 \leq Ri \leq 0,05$). Pour estimer le déplacement nul du plan, on a utilisé les méthodes de la conservation des masses ainsi que des moindres carrés. On a jugé que les résultats de la méthode de la conservation des masses, étaient très fiables et indiquaient la dépendance de d et de z_o par rapport à la vitesse du vent: d décroît et z_o s'accroît quand la vitesse du vent s'accroît. On a établi que le d moyen était de 13,43 ± 1,16 m (soit d/h = 0,67h, h étant la hauteur du couvert) et z_o etuit de 2,72 ± 0.87 m (soit $z_o/h = 0,14$). Pour déterminer les résistances aérodynamiques (r_a), on s'est servi des valuers de d et de z_o corrigées en fonction des effets de la vitesse du vent. Celles-cé furent comparées à celles déterminées en se servant de paramétres du profil constant souvent cités pour les récoltes agricoles, d/h = 0.63 et 20/h = 0,13 (Monteith 1973); et pour la forêt d/h = 0,76 et $z_o/h = 0,075$ (Jarvis et al. 1976). La résistance qui s'accroit (r_b) à été calculée en se servant de l'approximation $r_b = 4/u$, et en incluant l'équation de la résistance aérodynumique de la vapeur de l'eau r_{av}. Les valeurs de r_{av} avec les mesures indépendantes du rapport Bowen et du bilan énergétique de l'évaporation seront utilisées afin de déterminer la résistance superficielle r_c du modèle Penman-Monteith.

Introduction

Evaporation from a forest cover is important information for studies trying to anticipate the effects of surface cover changes or the moisture stress in a particular forest stand. Obtaining accurate estimates of evapotranspiration from a tall and heterogeneous crop such as a forest is undoubtedly difficult, especially if the regional topography is variable. One reliable and practical method of estimating evapotranspiration is the Penman-Monteith model. It's attractiveness as an applicable model to forest covers is attributed to the requirement of easily measurable meteorological data and the incorporation of a physical response of vegetation to control on evaporation. If meteorological data is available from several point sources and a database of surface cover is available, it may be used to obtain regional evaporation estimates. This makes the model particularly attractive for researchers who have use of a geographic information system (GIS).

The Penman-Monteith model requires, in addition to measured meteorological parameters, an estimate of

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

the vegetative control on evaporation and an estimate of the aerodynamic control on the transfer of water vapour from the surface to the overlying boundary layer. Because of the rough structure associated with forests, the mixing above the canopy tends to create lower aerodynamic resistances than for short and morphologically smooth crops. Aerodynamic resistance for momentum (r_{aM}) is often reported to be an order of magnitude less than surface resistance (r_s) (Stewart and Thom 1973), and because of its lower relative importance, is sometimes set to a constant value (e.g. Stewart and De Bruin 1985, Dolman et al. 1988). However, during periods low vapour pressure deficits, low available energy, or light winds its importance may be significantly greater. Furthermore, many studies often ignore the bluff body effects discussed by Chamberlain (1966) which present an extra resistance to aerodynamic exchange of heat and vapour over momentum.

The purpose of this study is to examine the aerodynamic parameters of a tall, mixed forest and at a later time evaluate if significant improvement in evaporation estimates from the Penman-Monteith model maybe obtained by considering r_{aM} as a variable. Determining r_{aM} requires a knowledge of the zero plane displacement (d) and surface roughness length (z_0) of the forest in addition to wind velocity at a reference level above the forest. Zero plane displacement and surface roughness length may be obtained from wind profile data above the forest.

Data

Data for this study was collected at a mixed forest site at the Petawawa National Forestry Institute (45° 58' N, 77° 25' W), near Chalk River, Ontario during 1987 (McCaughey 1989). A detailed biomass survey and site description has been previously presented by Mullins (1986), Saxton (1986) and Saxton and McCaughey (1988). These studies indicate the forest site is very heterogenous with respect to species age, type and distribution. However, despite this variation, the top of the canopy may be described as relatively closed (60 to 70% canopy cover) with a mean height of 20 m (Joiner 1988). Tree density is estimated at 6255 trees/ha, but it should be noted that 84% of this estimate represents lower canopy vegetation. Located at the site is a 39 m tower for the support of meteorological instrumentation. In 1987, anemometers were located at five levels: 26.04 m, 28.47 m, 30.74 m, 33.22 m and 37.72 m above the canopy. These anemometers were placed on two-metre booms on an orientation of 315°. Level four was used as the reference height (z_r) which also represented the top of the Reversing Temperature Difference Measuring System (RTDMS) used for Bowen ratio measurements. During the period from August 4 to September 5, 1987, wind profile data was averaged over 30 minute periods and recorded on a Campbell Scientific CR21 datalogger.

Theory

The convective fluxes between the surface and the atmosphere depend upon the turbulence generated in the boundary layer. The intensity of the mixing is controlled by the structure of the canopy and the wind speed, and can be parameterized from the wind profile. Most studies use the logarithmic model to describe the wind profile, which in differential form is,

$$\frac{du}{dz} = \frac{u_*}{k(z - d)}, \qquad (1)$$

where u_* is the friction velocity ($m.s^{-1}$), k is von Kármán's constant (0.41), d is the zero plane displacement (m). Equation (1) can be integrated to give the logarithmic wind profile as,

$$u(z) = \frac{u_*}{k} \ln \frac{z - d}{z_0}, \qquad (2)$$

where the surface roughness length (z_0) is the constant of integration. The size of z_0 indicates the bulk effectiveness of the plant community as a momentum absorber, while d can be considered as the upward displacement of the wind profile by the vegetation. The zero plane displacement must be included for profiles over tall vegetation since momentum absorption occurs at a significant height in comparison to the measurement height of profile data. It is often assumed that variations in the value of z_0 and d from period to period are likely to be negligible unless a substantial change in geometry occurs such as through growth or streamlining effects from strong winds (Thom 1975). Since Equation (2) is valid only for neutral conditions, values of d and z_0 are determined only for near-neutral conditions.

In this study, sampling periods with atmospheric stability in the range $0.05 \le Ri \le 0.05$ were considered to be sufficiently neutral, where Ri is the Richardson number. This assumption is in agreement with other work such as Oliver (1971) who found wind profiles above a 15.5 m tall pine forest in the range $0.05 < Ri < 0.10$ to follow a log form. Based upon this criteria a total of 368 profiles were selected for analysis from a total of 1442 profiles. Two methods were used to obtain measures of the zero plane displacement. One, referred to as the mass conservation method, is discussed by Tajchman (1981) and Molion and Moore (1983), and the other was the more traditionally used least squares regression method. The mass conservation approach assumes that airflow above the surface is incompressible and therefore the rate of mass flow from the ground to height z_1 above an open smooth surface is the same as the rate of mass flow from the ground to a height z_2 above the forest, as illustrated in Figure 1. Following the properties of mass conservation

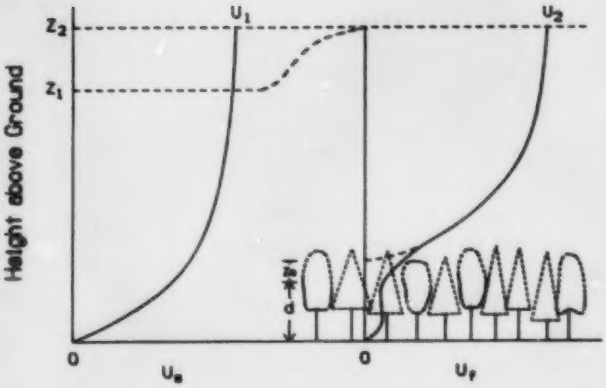


FIG 1. Idealized mean wind profiles for smooth and forested surfaces. Adopted from Tajchman (1981) and Raupach and Thom (1981).

$$\int_0^{z_2} u_s(z)\,dz = \int_0^{z_2} u_f(z)\,dz \tag{3}$$

where $u_s(z)$ and $u_f(z)$ are the wind velocities at height z above an open smooth surface and forest, respectively. If $u_s(z)$ and $u_f(z)$ are sufficiently high, the mean air stream velocity, U, above the smooth surface and forest will be almost equal, and Equation (3) becomes

$$\int_{z_1}^{z_2} u_s(z) = \int_0^{z_2} u_s(z)\,dz - \int_0^{z_2} u_f(z)\,dz \tag{4}$$

or,

$$z_2 - z_1 = \frac{1}{U}\int_0^{z_2} [u_s(z) - u_f(z)]\,dz \tag{5}$$

Under neutral conditions, the vertical profile above the smooth surface can be obtained with sufficient accuracy from

$$u_s(z) = U\frac{\ln(z_1/z_{0s})}{\ln(z_2/z_{0s})} \tag{6}$$

where z_{0s} is the roughness length above the smooth surface. Molion and Moore (1983) discuss this parameter in more detail. In this study it is assumed that z_{0s} = 0.05 m will suffice. This value was found to give reasonable results for the Thetford forest which had a height of 18.5 ± 1.5 m at the time of the study in 1980.

The vertical wind profile above the forest must be obtained from integrating point measurements above the forest canopy. For this analysis, the integrated form of Equation (5) presented by Molion and Moore (1983) was used. Using the trapezoidal rule, Equation (5) simplifies to

$$z_2 - z_1 = \left[z_2 - \frac{z_2 - z_{0s}}{\ln(z_2/z_{0s})}\right] - \left[\sum_{i=1}^{N} (u_i + u_{i-1})(z_i - z_{i-1}) + u_i z_i\right] \tag{7}$$

where u_i and z_i represent the measured wind velocity and height at level i, and N is the number of levels.

The more traditional approach to determine zero plane displacement is to optimize Equation (2) for d using the least squares regression method. With this method, ln(z-d), is plotted against wind velocity. Values of d are substituted iteratively and a linear regression line fitted by the least squares method until a minimum error in residuals is found. This method is very slow and subject to high variance since the results are very sensitive to profiles which do not fit the log model perfectly, but does not impose the physical significance of d that mass conservation does (Shuttleworth pers. comm.).

The relationship between d and z_0 to canopy height (h) depends upon the density and overall geometry of the individual roughness elements and may be regarded as characteristic of the canopy. If the surface is not too densely packed it is often assumed that d and z_0 are proportional to h. Jarvis et al. (1976) report normalized d and z_0 values from 15 coniferous forest stands which range between 0.67 h to 0.92 h for d and between 0.02 h and 0.14 h for z_0. Results from several of the sites reported by Jarvis and others are summarized in Table 1. Most studies are conducted on only near-neutral data but some extend over a wider range of stabilities. The wider range of values is largely a result of the vegetative structure and foliage density distribution, which for forests tends to be high in the upper canopy (e.g. Rauner 1976). The significantly higher d/h reported for Amazonian rainforest is not unexpected considering the tendency for tropical forests to have more foliage at higher levels than temperate forests.

There has not been agreement between all studies whether there is dependence between the profile parameters and wind speed or atmospheric stability for forests. Vogt and Jaeger (1988) found d to decrease and z_0 to increase with increasing wind speeds above Scots pine in the Hartheim/Rhine forest. This is in agreement with that presented by Rauner (1976) for a deciduous forest. The results from the Petawawa forest are also in agreement with this trend. However, not all studies have observed this relationship. Tajchman (1972) obtained a constant value of d, and found z_0 to decrease with increasing wind speeds. For an 11.5 m Sitka spruce forest, Landsberg and Jarvis (1973) found

Table 1. Zero plane displacement and surface roughness lengths for various forest sites.

Source	height (m)	d/h	z_0/h	vegetation type (location)
Campbell (1977)	-	0.64	0.13	many dense covers
Dolman (1986)	9.6	0.75	0.10	European Oak (Castricum, Neth.)
Landsberg and Jarvis (1973)	11.5	0.84	0.03	Sitka spruce (Aberdeen, Scotland)
Monteith (1973)	-	0.63	0.13	agriculture crops
Molion and Moore (1983)	18.5	0.72	0.07	Scots pine (Thetford, U.K.)
Molion et al. (1988)	35.0	0.88	0.06	rainforest (Central Amazon)
Sellers et al. (1988)	35.0	0.82	0.06	rainforest (Central Amazon)
Jaeger (1984)[1]	8.0	0.65	0.20	Scots pine (Hartheim, Germany)
Jarvis et al. (1976)	16.0	0.78	0.075	Scots pine (Thetford, U.K.)
Tajchman (1971)	27.2	0.71	0.10	Norway spruce (Munich, Germany)
Vogt and Jaeger (1988)[2]	10.5	0.70	0.07	Scots pine (Hartheim, Germany)
Present Study	20.0	0.67	0.135	mixed forest (P.N.F.I., Canada)

[1] Determined using Equations (9) and (12) and height in 1982.
[2] Taken from 1986 data presented in Figure 3.

only a slight decrease in d with increasing wind velocity, which was not great enough to require a wind speed correction to the drag coefficient (see Equation 9). In recent papers (e.g. Vogt and Jaeger 1988) it has been noted that the calculation of profile parameters is very sensitive to measurement errors in wind speed data. The same authors conclude that the contradictory conclusions between their study and the earlier analysis of Jaeger (1984) resulted from an insufficiently high measurement profile. After raising the height of their anemometers used to measure the wind profile data they found a significant dependence between wind speed and profile parameters. They suggest a plausible cause may be the increased depth of penetration (lower zero plane) and increasing surface roughness with increasing wind speed.

Evaluating accurate profile parameters is of considerable importance for obtaining accurate evapotranspiration estimates when using the aerodynamic method or analysis of stability functions. Vogt and Jaeger (1988) note a 10% difference in d leads to a similar difference in the evapotranspiration estimate. It is unlikely to be as critical in the Penman- Monteith approach because r_{aM} is usually less than 10% of the surface resistance for many forests. McNaughton and Black (1973) show that over a Douglas Fir forest, a 50% error in r_{aM} produces only a 3% error in the evapotranspiration estimates. In their worst case daytime situation the maximum uncertainty in r_c arising from error in r_{aM} is ± 8 $s \cdot m^{-1}$, which is small in comparison to diurnal and daily differences.

The effect of the forest structure on the exchange of momentum between the canopy and the air above it may be represented by combining the canopy aerodynamic parameters (z_0 and d) into an aerodynamic resistance for momentum (r_{aM}). Under conditions of neutral stability and sufficiently large fetch, the resistance to the transfer of momentum is

$$r_{aM} = \frac{[\ln(z_r - d)/z_0)]^2}{k^2\, u(z_r)} . \qquad (8)$$

where z_r represents a reference height above the canopy for measuring wind velocity. It is also useful to express Equation (8) in terms of the low level drag coefficient C_{aM}, where:

$$r_{aM} = \frac{1}{u(z_r)}\, C_{aM}^{-1} . \qquad (9)$$

It has been shown by several studies (e.g. Bradley 1971/72) that over agricultural crops, C_{aM} is effectively constant over a wide range of instabilities because the large wind shear near the surface reduces the distortion of the wind profile by buoyancy effects. Thus, eddy conductivity to momentum may be taken as linearly proportional to wind speed if there are reliable estimates of z_0 and d over a range of stabilities. The range of C_{aM} values reported by Jarvis et al. (1976) for coniferous forest is wide, but most fall in the range 0.06 to 0.16. They suggest a convenient approximation is, $C_{aM} \approx 0.1$. It follows that,

$$r_{aM} \approx 10 \cdot 1/u(h) . \qquad (10)$$

Milne et al. (1985) disregard the influence of wind speed if velocities are less than 1 $m \cdot s^{-1}$. At such low wind speeds, the errors resulting from stalling and non-log wind profiles are likely to be far greater the boundary layer resistances. If there is a dependence between z_0 or d and wind speed or stability, as there appears to be for some forests, then C_{aM} should be treated also as a variable.

The aerodynamic resistance to the transfer of momentum from the air to elements in the canopy is always less than the resistance to the exchange of sensible or latent heat. This is attributed to the effect of normal pressures on individual elements of the canopy which considerably augment the drag forces generated by molecular diffusion of momentum, also referred to as the 'bluff-body' effect. In consideration of this, Chamberlain (1966) suggests the addition of an extra resistance term (r_b), to account for the excess resistance to water vapour and sensible heat exchange. The value of r_b is approximated by $4/u_*$ (Stewart and

Thom 1973). It will be assumed that this determination of r_b is adequate for the Petawawa forest. Thus, the resistances for latent and sensible heat exchange (r_{aV} and r_{aH}, respectively) are,

$$r_{aH} = r_{aV} = \frac{[\ln((z_r-d)/z_0)]^2}{k^2\, u(z_r)} + r_b\,. \qquad (11)$$

Results

The seasonal mean estimates of d and z_0 obtained using the mass conservation method were found to be 13.4 ± 1.6 m and 2.7 ± 0.9 m, respectively, or when normalized to canopy height (h), d=0.67/h and z_0=0.135/h (Table 1). Figures 2 and 3 show the dependence of these parameters with wind speed above the canopy. It was observed that d decreased to a maximum depth of penetration with increasing wind velocity, and z_0 increased. The rate of decrease in d is much greater at wind velocities below 5 $m\bullet s^{-1}$. For wind speeds greater than 5 $m\bullet s^{-1}$, the rate of decrease becomes less, and is likely a result of the streamlining of the canopy and indicates a levelling off to a maximum level of penetration. It has also been suggested that the minimum zero plane displacement is associated with the maximum leaf area index of the canopy (Rauner 1976). The decision to break the relationship at 5 $m\bullet s^{-1}$ is based upon a non-linear regression analysis which indicated a minimum standard error near this value.

Regression analysis of d and z_0 was performed to obtain parameters for the linear equations shown in Figures 2 and 3. These equations were applied to estimates of r_{aH}. It was necessary to omit z_0 values greater than 5 m since these values had undue influence on the regression equation and have little physical support.

The method of mass conservation was preferred over the more traditional least squares approach since results obtained by optimizing d were more sensitive to small measurement errors. Many profiles could not be used to find d using least squares, and for many when a minimum d could be found, the value was often unrealistic. Figure 4 shows the dependence of d calculated by the least squares regression method on wind velocity. The scatter of d estimates indicate that no significant dependence of d on wind speed was observed. For the same sampling period used in the mass conservation analysis, the method of least squares estimate of d was 14.38 ± 4.3 m and z_0 was 0.9 ± 1.1 m, or d/h = 0.72 and z_0 = 0.05. These mean values are closer to those reported for other forests than those obtained by mass conservation (Table 1). However, the variance was too great to allow any degree of confidence in the results.

The influence of canopy geometry on aerodynamic parameters is difficult to evaluate for a single site since profile parameters and canopy geometry are variable. In this study zero plane displacement and mean wind speed for the neutral profiles were grouped by prevailing wind direction into eight compass bearings (Figures 5 and 6). Figure 7 shows the distribution of middle and upper canopy trees in relation to the

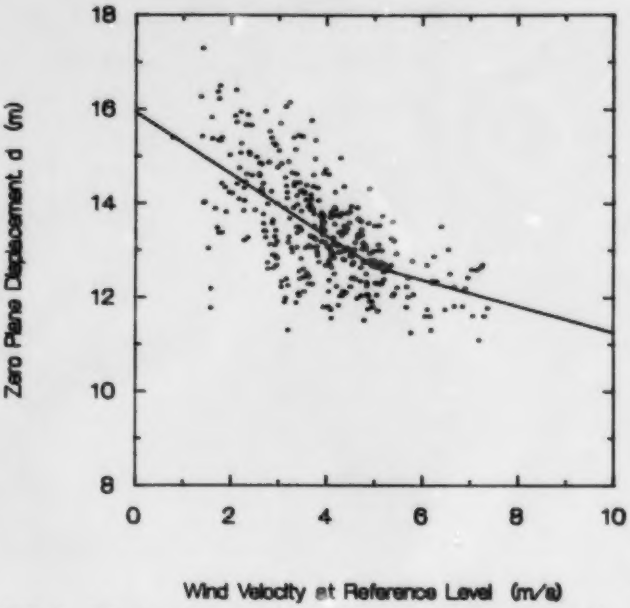


FIG 2. Relationship between d and wind velocity measured at z_r. Zero plane displacement was determined by the mass conservation method. The solid line represents the linear equation used to estimate d. Equation parameters are given in Table 2.

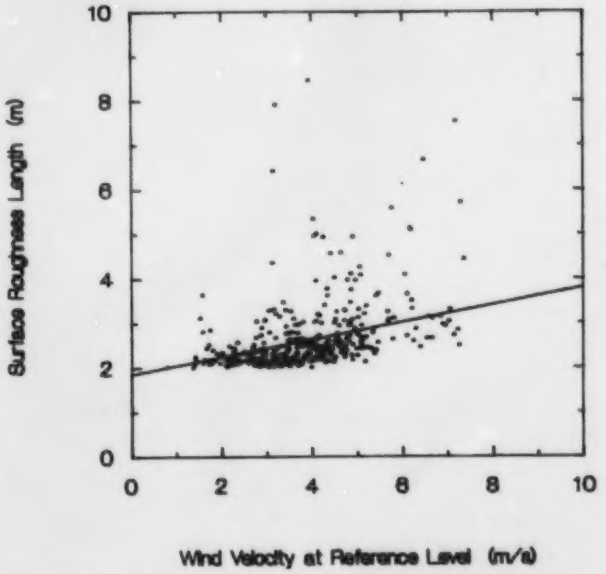


FIG 3. Dependence of roughness length on wind speed at z_r. The linear equation z_0 = 1.859 + 0.195 $u(z_r)$, was determined from z_0 values less than 5 m.

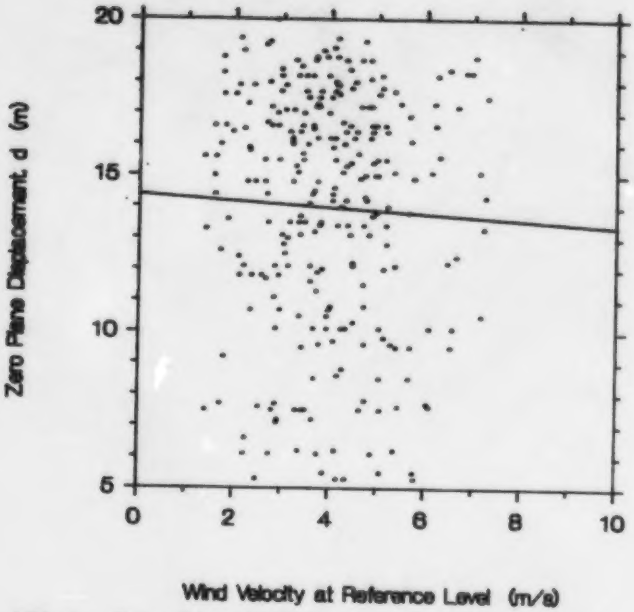


FIG 4. Zero plane displacement values obtained from optimizing Equation (2) for d in relation to wind speed at level z_r. The slope of the line of best fit is not signifcantly different from zero.

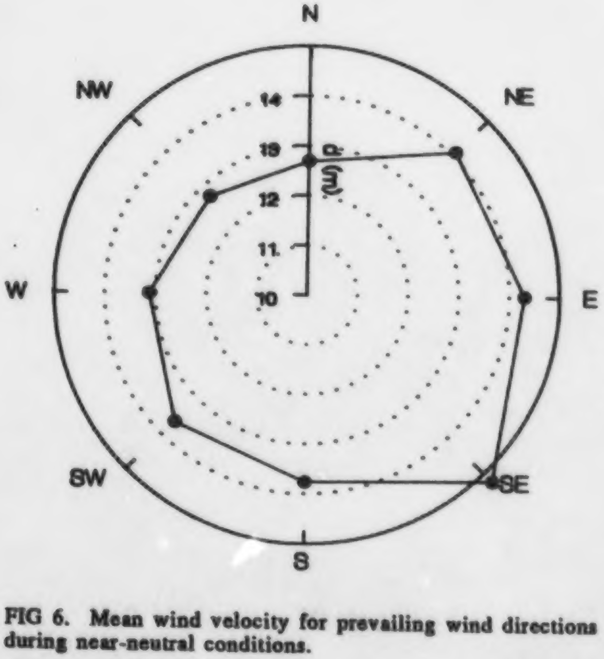


FIG 6. Mean wind velocity for prevailing wind directions during near-neutral conditions.

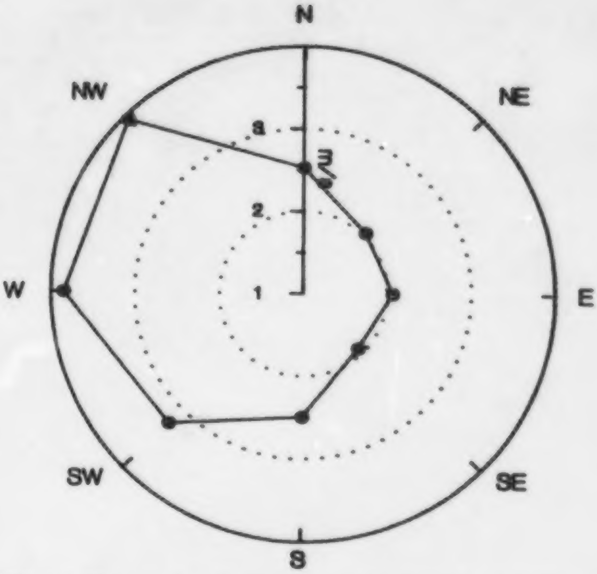


FIG 5. Mean zero plane displacement determined by mass conservation method grouped by prevailing wind direction. See Table 2 for number of profiles from each direction.

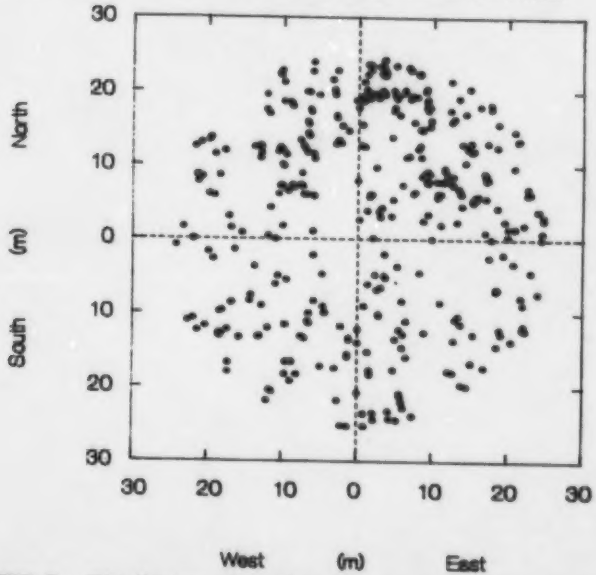


FIG 7. Distribution of middle and upper canopy trees in relation to the instrumentation tower. Data was collected for a biomass survey by Saxton (1986).

instrumentation tower. This data was recorded in a biomass survey during 1985 by Saxton (1986). Although this survey only covers a 25 m radius and does not show explicitly the density of the canopy surface, it does indicate the presence of numerous larger trees in the north-east quadrant. It was expected that if this high density in tree spacing is representative of a tightly closed canopy in this direction from the tower, that an increase in d may be observed as a result of the higher leaf area index. If the assumption is made that zero plane displacement is equal for all prevailing wind directions, it is expected that the residuals will be normally distributed and any deviation may be attributed to the geometry of the canopy. The results which are given in Table 2 show no evidence to support the claim that canopy geometry on a small scale influences the size of d. Perhaps, if more detailed information on upper canopy structure was available on a larger scale, the influence of canopy geometry might be evident.

Table 2. Mean profile parameters and wind velocities for prevailing wind directions.

Dir	N	u (m s^{-1})	d (m)	z_0 (m)	$\hat{d}$ (m)	Residual
N	15	4.31	12.67	2.99	13.90	-1.23
NE	3	1.90	14.10	2.33	14.67	-0.57
E	12	1.99	14.30	2.43	14.62	-0.32
SE	22	2.24	15.26	2.16	14.45	0.81
S	62	3.34	13.76	2.44	13.73	0.03
SW	65	3.90	13.64	2.49	13.36	0.28
W	109	4.21	13.12	3.01	13.15	-0.03
NW	63	4.76	12.76	2.94	12.79	-0.03
Total	351					
Mean		3.88	13.43	2.72		

Notes:

i. Wind velocity represents mean velocity for neutral profiles only.

ii. $\hat{d} = 15.927 - 0.659\ u(z_r)$, if $u(z_r) < 5$ m s^{-1}

$\hat{d} = 14.017 - 0.277\ u(z_r)$, if $u(z_r) \geq 5$ m s^{-1}

iii. N = number of profiles

Aerodynamic resistances were determined for 30-minute periods using the wind speed dependent relations for d and z_0 shown in Figures 2 and 3. Wind speed data from level four was normally reliable for each half-hour, but if the wind speed value was missing then the daily mean wind speed was substituted for that 30-minute period. It was necessary to calculate a complete daily record since the r_{aV} data is required to calculate surface resistance values which will be used later. The mean half-hourly values of aerodynamic resistance for water vapour r_{aV} and momentum r_{aM} are shown in Figure 8, along with the mean wind speed at z_r. The daytime means (0600 hr to 1800 hr) of raV and raM were 17.08 ± 8.4 s•m^{-1} and 10.94 ± 6.66 s•m^{-1}, respectively. Because wind speed generally increases throughout the morning and declines in late afternoon, r_{aM} also follows a regular pattern. Thus, setting r_{aV} to a constant or mean value in the Penman-Monteith model will result in a small overestimate of evaporation in the morning and underestimate in the afternoon. This may be negligible during the afternoon, depending upon conditions, since r_s increases continually throughout the daytime period and available energy is greatest during the afternoon. However, in the morning when r_s and the available energy are low, the influence may be significantly greater.

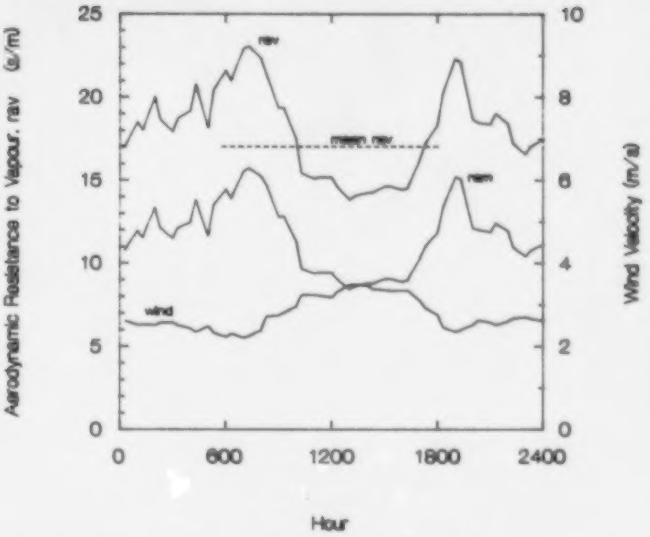


FIG 8. Mean daily behaviour of aerodynamic resistance for momentum r_{aM} and water vapour r_{aV} between August 4 and September 5, 1987 along wind mean wind velocity at z_r. Values represent resistances determined for both neutral and non-neutral periods. The mean r_{aV} was determined for the daytime period 0600 to 1800 hr.

The aerodynamic parameters for the daytime period of August 17 are reproduced in Table 3. This day was chosen as an example since it had steady winds throughout the day that are analogous to the mean wind behaviour and because it was a day of predominantly neutral stability. The values of d and z_0 are measured values using the mass conservation method and r_{aM} was calculated from these values.

Figure 9 shows the decrease in the inverse of the drag coefficient with increasing wind speed that results from lower d and higher z_0 values (ie. lower sink for momentum) with increasing wind speed. r_{aM} determined from the wind dependent relation shown in Figure 9 was compared to estimates of r_{aM} obtained using the general relationships d/h=0.63 and z_0/h=0.13 reported by Monteith (1973) as representative of many crops and d/h=0.76 and z_0/h=0.075 reported by Jarvis et al. (1976) for the Thetford forest and representative of many other forests. For these approximations, C_{aM}^{-1} at z_r are 25.51 and 36.77, respectively. The relationship between r_{aM} and wind speed determined for both of these empirical approximations and wind dependent profile parameters for the Petawawa forest appear in Figure 10.

Summary

Under conditions of light winds, low available energy or low humidity deficit, the evaporative demand is not expected to be high, however, the aerodynamic

Table 3. Aerodynamic Parameters during the daytime period for August 17, 1987.

hour	wind ($m \cdot s^{-1}$)	Ri	$\hat{d}$ (m)	z_0 (m)	$1/C_{aM}$	r_{aM} ($s \cdot m^{-1}$)	r_{aM} ($s \cdot m^{-1}$)
600	2.10	.10	-	-	-	-	12.61
630	2.08	.07	-	-	-	-	12.70
700	1.86	-.03	14.34	2.18	27.72	14.91	14.37
730	1.79	-.31	-	-	-	-	14.99
800	1.96	-.06	-	-	-	-	13.61
830	2.93	.00	12.88	2.56	25.55	8.62	8.69
900	2.71	-.01	13.41	2.36	26.93	9.94	9.47
930	1.78	.56	-	-	-	-	15.12
1000	2.29	-.02	14.46	2.21	27.21	11.88	11.45
1030	3.88	-.06	-	-	-	-	6.29
1100	3.53	-.02	12.13	3.27	20.67	5.86	7.02
1130	4.24	-.04	11.83	4.94	12.78	3.01	5.67
1200	3.42	-.03	12.40	2.93	22.87	6.69	7.28
1230	4.36	-.10	-	-	-	-	5.49
1300	4.99	-.02	12.79	2.76	23.84	4.78	4.70
1330	3.98	-.02	14.72	2.02	29.18	7.33	6.12
1400	4.90	-.03	11.93	4.95	12.66	2.58	4.80
1430	4.16	-.02	13.56	2.41	26.21	6.30	5.81
1500	4.89	.00	12.78	3.09	21.23	4.34	4.81
1530	4.52	.01	13.01	2.56	25.40	5.62	5.27
1600	5.33	.00	12.69	2.79	23.70	4.46	4.31
1630	5.46	-.01	12.20	3.68	18.06	3.31	4.17
1700	5.08	-.02	13.01	2.51	25.88	5.10	4.58
1730	4.09	-.02	12.63	3.06	21.62	5.29	5.92
1800	3.79	-.01	12.98	2.49	26.12	6.89	6.48

Note: r_{aM} was determined from mass conservation results for the individual time periods, and r_{aM} represents estimated values using the relations shown in Figures 2 and 3 (i.e. mean conditions)

resistance to water vapour may present a significantly greater control on the evaporation that is occurring under these conditions. It was observed that r_{aM} generally decreased over the daytime period until late afternoon as a result of increasing wind velocity during the day. Mean values of r_{aV} for the morning (0600 to 1130 hr) were 19.5 $s \cdot m^{-1}$ and fell to 15.09 $s \cdot m^{-1}$ during the afternoon (1200 to 1800 hr) with a daytime mean of 17.03 $s \cdot m^{-1}$.

Estimates of r_{aM} were obtained using the drag coefficient relationship dependent upon wind speed. Estimates of d and z_0 obtained by the method of mass conservation revealed that decreased and z_0 increased with increasing wind velocity. A linear equation was determined for the z_0 data set and two linear equations fitted to d for data below and above 5 $m \cdot s^{-1}$. The slower decline in d at higher wind speeds may be a result of canopy streamlining and the presence of the maximum foliage density level.

The profile parameters d and z_0 were estimated by optimizing d for the log profile model and by applying the method of mass conservation. Estimates of d/h and z_0/h obtained by mass conservation were slightly lower and higher, respectively than those reported for other forests, but were considered to be more reliable than those obtained by least squares. The mean estimates of d/h and z_0/h obtained from least squares were similar to those reported elsewhere, but the method is very subjective and sensitive to slight deviations from the log model. This resulted in many seemly profiles being discarded and a large variance of d and z_0 values. Numerous past studies have used least squares to estimate profile parameters, however, recently, several studies have applied the method of mass conservation (e.g. Molion et al. 1988) or other methods (see Seller et al. 1988).

Acknowledgements

I would like to thank Dr. J.H. McCaughey for his assistance in preparing this manuscript and guidance as an academic supervisor. Gratitude is also extended to the Queen's University School of Graduate Studies, who provided financial assistance to attend this conference.

The data analysis was performed using Waterloo Fortran IV and Systat V4.0 (#3250 112). All plots were produced using Sygraph V1.0 (#3250 011) except

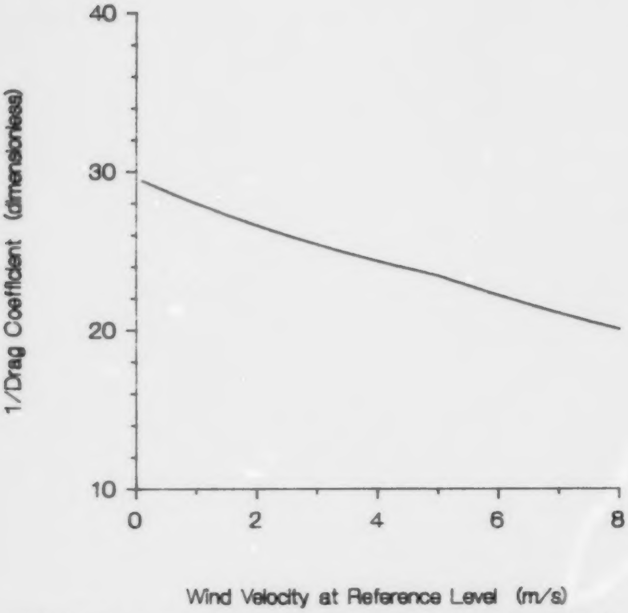


FIG 9. The inverse of the drag coefficient at z_r determined for wind speed dependent d and z_0. For comparison, C_{aM}^{-1} with d/h=0.63 and z_0/h=0.13 (eg. Monteith, 1973) is 25.51, and with d/h=0.76 and z_0/h=0.075 (eg. for Thetford forest (Jarvis et al. 1976)) it is 36.77.

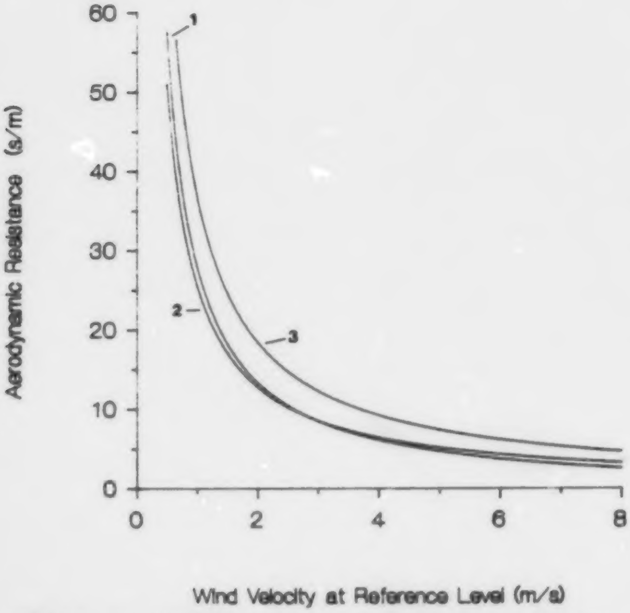


FIG 10. Aerodynamic resistance to momentum (r_{aM}) versus wind velocity. Line 1 is for the Petawawa data using the wind speed dependent drag coefficient, line 2 represents the relationship using the empirical relations d/h=0.63 and z_0/h=0.13, and line 3 was obtained using relationships representative of those often quoted for other forests, d/h=0.76 and z_0/h=0.075 (See Table 1).

for Figure 1 which was drawn with Easycad V1.1 (Evolution Computing) and the manuscript was prepared with WordPerfect V5.0 (WP044587567).

References

BRADLEY, E.F. 1971/72. The influence of thermal stability on a drag coefficient measured close to the ground. Argic. Meteorol. 9:183-190.

CAMPBELL, G.S. 1977. An introduction to environmental biophysics. New York: Springer-Verlag.

CHAMBERLAIN, A.C. 1966. Transport of gases to and from grass and grass like surfaces. Proc. R. Soc. Lond. A290:236-260.

DOLMAN, A.J. 1986. Estimates of roughness length and zero plane displacement for a foliated and non-foliated oak canopy. Agric. For. Meteorol. 36:241-248.

DOLMAN, A.J., J.B. STEWART, AND J.D. COOPER. 1988. Predicting forest transpiration from climatological data. Agric. For. Meteorol. 42:339-353.

JAEGER, L. 1984. Climatology of wind profile parameter estimates above a growing pine forest. Arch. Met. Geoph. Biocl. Ser. B34, 163-179.

JARVIS, P.G., G.B. JAMES, AND J.J. LANDSBERG. 1976. Coniferous forest. P. 171-240 In J.L. Monteith, ed., Vegetation and the Atmosphere, Vol. 2, Academic Press, London.

JOINER, D.W. 1988. Energy balance and eddy correlation measurements over a mixed forest, Chalk River, Ontario. M.Sc. Thesis. Queen's University, Kingston, Ontario, 114pp.

LANDSBERG J.J., and P.G. JARVIS. 1973. A numerical investigation of the momentum balance of a spruce forest. J. of Appl. Ecology. 10:645-655.

MCCAUGHEY, J.H. 1989. Energy exchange for a forest site and a clear-cut site at Chalk River, Ontario. Can. Geographer. (In press).

MCNAUGHTON, K.G., AND T.A. BLACK. 1973. A study of evapotranspiration from a Douglas-Fir forest using the energy balance approach. Water Resour. Res. 9:1579-1590.

MILNE, R., J.D. DEANS, E.D. FORD, P.G. JARVIS, J. LEVERENZ AND D. WHITEHEAD. 1985. A comparison of two methods of estimating transpiration rates from a sitka spruce plantation. Boundary-Layer Meteorol. 32:155-175.

MOLION, L.C.B., A.O. MANZI, V. VISWANADHAM, L.D.A. SA, V.P. SILVA FILHO, C.A. NOBRE, J.L.M. NOGUEIRA, R.G.B. ANDRE, A.O. MARQUES FILHO, A.P. FATTORI AND M. JANUARIO. 1988. Micrometeorological measurements in Amazonian forest during GTE/Able-2A Mission. J. Geophys. Res. (In press).

MOLION, L.C.B., AND C.J. MOORE. 1983. Estimating the zero-plane displacement for tall vegetation using a mass conservation method. Boundary-Layer Meteorol. 26:115-125.

MONTEITH, J.L. 1973. Principles of Environmental Physics. Edward Arnold. London. 241pp.

MULLINS, D.W. 1986. Evapotranspiration study of forest and clear-cut sites, Chalk River, Ontario. M.Sc. Thesis. Queen's University, Kingston, Ontario, 128pp.

OLIVER, H.R. 1971. Wind profiles in and above a forest canopy. Quart. J. R. Met. Soc. 97:548-553.

RAUNER, J.J. 1976. Deciduous forests. P. 241-264 In J.L. Monteith, ed., Vegetation and the Atmosphere, Vol.2 Academic Press, London.

RAUPACH, M.R., AND A.S. Thom. 1981. Turbulence in and above plant canopies. Ann. Rev. Fluid Mech. 13:97-129.

SAXTON, W.L. 1986. The measurement of canopy storage terms in the energy balance of a mixed forest, Chalk River, Ontario. M.Sc. Thesis. Queen's University, Kingston, 115pp.

SAXTON, W.L., AND J.H. MCCAUGHEY. 1988. Measurement considerations and trends in biomass heat storage of a mixed forest. Can. J. For. Res. 18(2):143-149.

SELLERS, P.J., W.J. SHUTTLEWORTH, J.L. DORMAN, A. DALCHER AND J.M. ROBERTS. 1988. Calibrating the simple biosphere model (SiB) for Amazonian data; Part 1, average calibration with field data. J. Clim. Appl. Meteorol. (In press).

STEWART, J.B., AND H.A.R. DEBRUIN. 1985. Preliminary study of dependence of surface conductance of Thetford forest on environmental conditions. P. 91-104 In B.A. Hutchison and B.B. Hicks, eds., The Forest-Atmosphere Interaction, D. Reidel Publ. Co.

STEWART, J.B., AND A.S. THOM. 1973. Energy budgets in pine forest. Quart. J. R. Met. Soc. 99:154-170.

SZEICZ, G., AND I.F. LONG. 1969. Surface resistance of crop canopies. Water Resour. Res. 5:622-633.

TAJCHMAN, S. 1972. The radiation and energy balances of coniferous and deciduous forest. J. Appl. Ecology. 9:359-375.

TAJCHMAN, S.J. 1971. Evapotranspiration and energy balances of forest and field. Water Resour. Res. 7(3):511-523.

TAJCHMAN, S.J. 1981. Comments on measuring turbulent exchange within and above forest canopy. Bull. Amer. Met. Soc. 62(11):1550-1559.

THOM, A.S. 1975. Momentum, mass and heat exchange of plant communities. P. 57-109 In J.L. Monteith, ed., Vegetation and the Atmosphere, Vol.1, Academic Press, London.

VOGT, R., AND L. JAEGER. 1988. Evaporation from a pine forest - applications of the Bowen ratio and the Monin-Obuchiv method. Agric. and For. Meteorol. (In press).

Use of Minisonde Observations for On-Site Fire Behavior Prediction

R.W. BURKE
Ontario Ministry of Natural Resources
Timmins, Ontario

P.C. WARD
Ontario Ministry of Natural Resources
Sault Ste. Marie, Ontario

Abstract

Upper level winds can have a significant impact on the behaviour of wildfires and prescribed burns. They may influence smoke column dynamics; on occasion, strong upper winds may be mixed to the surface, causing unexpected severe fire behaviour. In 1983, the fire management program in Ontario began using portable minisondes to obtain on-site upper air observations on prescribed burns and wildfires. A disposable transmitter attached to a pilot balloon relays temperature data to the earth station, while theodolite observations are used to track wind directions and speed during the ascent. Regional weather technicians carry out the observations and provide interpretation of the results to the fire boss. The minisonde data are used together with surface observations and forecasts to help determine the advisability, timing and location of prescribed burn ignition, and to predict the behaviour of the prescribed burn or wildfire. Minisonde units are located in each of the five Ontario fire regions. The regional weather technicians are proficient at analyzing the wind/temperature profiles, but further research into the relationship between the sonde data and smoke column and fire behaviour would be useful.

Résumé

Les vents soufflant en altitude peuvent avoir un impact important sur le comportement des feux de friches et des brûlages dirigés. Ils peuvent influencer la dynamique de la colonne de fumée; il arrive quelquefois que des vents forts en altitude puissent être attirés à la surface, donnant à l'incendie un comportement intense imprévu. En 1983, le programme de gestion des incendies de l'Ontario commençait à utiliser une minisonde portable pour obtenir des observations en altitude sur les lieux mêmes d'un brûlage dirigé et de feu de friches. Un émetteur de service fixé au ballon transmet des données sur la température à une station au sol tandis que des observations au théodolite servent à dépister la direction et la vitesse du vent lors de l'ascension. Les techniciens régionaux en météorologie effectuent les observations et assurent l'interprétation des résultats pour le chef de lutte. Les données de la minisonde sont utilisées de concert avec les observations en surface et les prévisions pour aider à déterminer l'opportunité, l'heure et l'endroit d'allumage d'un brûlage dirigé et pour prédire le comportement du brûlage dirigé ou d'un feu de friches. Chacune des cinq régions de gestion des feux de forêt de l'Ontario dispose de minisondes. Les techniciens en météorologie des régions ont la compétence voulue pour analyser les profils du vent/de la température, mais des recherches plus approfondies sur la relation entre les données des minisondes et la colonne de fumée et le comportement du feu seraient fort utiles.

Introduction

Vertical air temperature, wind speed and direction profiles above the earth's surface have a significant effect on the behaviour of wildfires and prescribed burns. In 1983, the fire management program of the Ontario Ministry of Natural Resources (OMNR) began using portable sounding devices to obtain data on upper air temperature and wind conditions over prescribed burn (PB) sites and project fires. These "minisonde" observations are used to help guide decisions on prescribed fire ignition (eg. advisability, timing), and to help predict fire behaviour and the possibility of erratic fire conditions on PBs and wildfires.

Requirement for Upper Air Observations

The vertical temperature profile (air temperature readings at increasing height) above surface is an indicator of atmospheric stability. Stability above the surface greatly influences the dynamics of the convection column above a fire. Large columns are often associated with intense fires with high energy outputs.

The vertical wind profile above the fire also has an important influence on fire behaviour. While surface winds affect the direction and rate of fire spread, upper winds can influence smoke column dynamics, including

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

the height of the column, its angle of rise, and the consequent potential for whirlwinds, spotting and other effects.

Atmospheric conditions can contribute to erratic fire behaviour, such as the development of fire whirlwinds and long-range spotting. Byram (1954) identified atmospheric conditions and wind profiles that were associated with certain "blow-up" fires in the United States. He found that an unstable air mass and wind speeds which decreased with height above ground favoured the formation of large, vertical convection columns, with a large-scale conversion of heat energy from the fire into turbulent motion in the column. These fires all demonstrated intense burning conditions and erratic behaviour, often more severe than expected given the surface weather and fuel conditions.

Byram presented a preliminary set of wind speed profiles that signalled potential trouble, and suggested that the use of on-site pilot balloon ascents would be a useful tool for fire management organizations.

Brotak (1977) suggested that some of Byram's contentions and original wind data were questionable. Brotak did find that strong gradient winds above the surface and macro-scale instability were commonly associated with the sixty large wildland fires studied in the eastern United States. In any event, knowledge of the upper air conditions seems necessary for the accurate prediction of potential fire behaviour.

Sources of Upper Air Data in Ontario

Fire managers in Ontario have long used available sources of upper air data to aid their fire behaviour predictions. Forecasts provided by the federal Atmospheric Environment Service and analysis provided by OMNR fire weather technicians include projections of atmospheric stability and upper level winds over broad areas. However, local observations or forecasts of these parameters are difficult to obtain, as there are only three upper air observing stations in the area of the Ontario fire region, and each station provides only two observations per day.

The need for upper air data became more acute in the early 1980's as the prescribed burning program in the province expanded. The number and average size of burns increased. There was an increasing trend towards the use of centre-fire ignition, where the initial ignition takes place in the interior of the burn area to induce formation of a convection column that will draw the succeeding ignition lines from the burn boundary towards the interior of the burn.

In this situation, the ignition boss on the burn needs conditions that are conducive to forming and sustaining the column, but without reaching intensity levels where control over the burn is lost. Lacking on-site data about the temperature and wind profiles above the surface, the fire manager faces uncertainty about the advisability and timing of burn ignition and the potential for unexpected behaviour problems.

In 1982, unexpected erratic fire behaviour was experienced on a prescribed burn in north central Ontario, triggered by a very rapid increase in air temperature, decrease in relative humidity, a sharp shift in surface wind direction, and increase in wind speed that occurred about one hour after ignition. Later analysis by the OMNR regional weather technician showed that a strong subsidence inversion was present over the fire, with the boundary of the inversion very close to the surface. As the heat released by the fire penetrated the inversion layer, the overlying hot, dry and windy air mass was brought to the surface. (A subsidence inversion occurs when a high pressure system in the troposphere descends toward the earth's surface, warming adiabatically as it subsides).

Initial Minisonde Evaluation

The 1982 fire experience triggered the investigating weather technician, L. Lacharity, to consider the methods available for on-site observation of upper air conditions. Lacharity suggested that the portable minisonde systems, used by some military and civilian meteorological agencies, could be adapted for use in forest fire management.

These minisondes transmit temperature data back to a radio receiver from a disposable transponder attached to a 1-metre helium pilot balloon. The temperature trace is plotted automatically on a chart recorder connected to the receiver.

By tracking the pilot balloon ascent with a theodolite and assuming a constant rate of rise of 180 m/min, the wind speed and direction profiles can also be calculated. Hand-held computers allow these calculations to be easily done on-site immediately following the ascent. The wind profile is then manually plotted alongside the temperature trace to obtain an overall impression of the atmospheric conditions above the fire.

One minisonde unit was acquired in 1983 for evaluation. Lacharity and his colleague H. Wailes, another regional weather technician, made observations at a number of prescribed burns and wildfires, and developed techniques for the use of the unit and researched the interpretation of the sounding data.

The minisonde project was immediately successful. Fire managers quickly accepted the use of this tool, and subsequently, additional units were obtained for all five of Ontario's fire regions.

Operation of the Minisonde Unit

The minisonde unit consists of a radio receiver/temperature recorder, helium tank and balloon-filling station, theodolite, and a supply of balloons and temperature transponders (Figure 1). The weather technician typically transports the unit in a truck camper, which provides both a work station and overnight accommodation for the technician.

Use of the minisonde can be requested for both prescribed burns and wildfires. The weather technician

Figure 1. Minisonde equipment. From left, foreground: Temperature chart recorder, balloon and filling station, radio receiver. Background: radio antenna, handheld computer.

selects an appropriate site and deploys the equipment. On prescribed burns a minimum of three ascents is usually desired, one about mid-morning, the second just prior to the planned ignition time, and the third about midway through the burn.

Use and Interpretation of the Minisonde Data

The minisonde data provides the weather technician with a supplement to other on-site observations and forecast information. The weather technician uses the sounding data to determine the degree of atmospheric stability above the fire, the presence of inversion layers, and wind speed and direction changes aloft. He can then advise the fire manager on how the ignition process (in the case of a prescribed burn) and fire behaviour may be affected by the upper air conditions. On a PB, the fire boss/ignition boss will take this into account when deciding whether to proceed with ignition, and determining the timing and rate of ignition.

The degree of stability affects the ease of ignition and formation of the convection column. For most prescribed burning applications (particularly when the centre-fire technique is employed), a moderate degree of instability is desirable. This will favour the formation of a convection column that will sustain the growth of the fire while carrying the smoke aloft.

A very unstable atmosphere may cause concern, as it encourages very turbulent motion in the column and may lead to erratic behaviour. Very stable conditions are also to be avoided, particularly when a convection burn has been prescribed, since the stability dampens the convective process, causes the smoke to settle out close to the ground, and often results in slow burning conditions.

The temperature profile will also indicate the presence of inversion layers. Inversions over a fire can be troublesome in several ways. The smoke will settle out at the inversion layer. As with any stable condition, convective activity will also be suppressed. This will be a problem if the inversion layer is close to the surface. The occurrence of fire whirlwinds have been found to be related to the presence of an inversion layer (McRae 1988).

A deep inversion layer, in the form of a subsidence or frontal inversion, can lead to unexpected fire behaviour problems if the inversion base is within 1000 m or so of the surface. If the convection column has sufficient energy to penetrate the inversion layer, the inversion may break down and the characteristics of the overlying air mass will be mixed down to the earth's surface. This may result in significant changes in temperature, relative humidity, and wind speed and direction, over a very short period of time, as experienced on the previously cited 1982 PB in northern Ontario.

The wind profile provided by the minisonde also gives the fire manager important information for predicting fire development and behavior characteristics. The winds aloft can have a significant effect on the fire, primarily through the interaction with the convection column.

The weather technician will be alert for profiles similar to the "trouble-makers" identified by Byram, where the wind speed reaches a peak at or just above the surface and then remains constant or decreases with height. Byram suggested that these negative wind shears are most problematic when the surface winds are of moderate strength (25-35 km/h, measured in the open).

These conditions are suitable for the development of large, vertical convection columns that may become very turbulent if sufficient heat energy is being released into the column from the fire. If this wind situation is present at a prescribed burn site, the fire boss may have to monitor the rate of ignition very closely to keep the rate of energy release below the critical level where the column dynamics dominate the behaviour of the fire. Otherwise, erratic behavior, including fire whirls and long-range spotting may occur.

The technician will also be alert to the presence of very strong winds near the earth's surface. These may affect the desired development of the convection column on a prescribed burn (ie. by "pushing" the column over before it is fully developed). This could lead to smoke problems on the leeward side of the fire, as well as fire spotting. Strong winds aloft coupled with a low-level inversion layer could also result, as previously discussed, in changes in wind speed and direction at the surface when the inversion breaks down.

A mid-morning ascent provides a good indicator of the surface conditions to be expected by mid-afternoon. The upper level winds can be used to forecast the afternoon surface wind speeds, and potential maximum wind speeds and the presence of low level jets. Afternoon surface temperatures and relative humidity can also be reliably estimated from the morning upper air conditions.

Future Development

Use of the minisonde data for predicting fire behaviour and identifying the potential for problem fire situations has been of significant benefit to fire managers in Ontario. However, the minisonde program is still in a developing stage. Its effectiveness is very dependent on the skills and interpretive knowledge of the weather technicians who operate the equipment.

There is a need to provide more interpretive and quantitative analysis tools for both the weather technician and the fire manager. We need a better understanding of the relationships between surface and upper air conditions and their interactions with the fire and the convection column, and in the case of prescribed burning, how ignition devices, patterns and timing can be used to achieve the desired level of fire intensity and behaviour.

The minisonde program provides a large number of quantitative upper air observations that can be related to observed fire behaviour. We now need to use this data and our experience to develop an objective system relating the vertical structure of the atmosphere to expected fire behaviour.

References

BROTAK, E.A. 1977. A synoptic study of the meteorological conditions associated with major wildland fires. Ph.D. dissertation, Yale University. 163 p.

BYRAM, G.M. 1954. Atmospheric conditions related to blowup fires. U.S.D.A., Forest Service, Southeastern Forest Experiment Station, Station Paper No. 35. 34 p.

MERRILL, D.F. and M.E. ALEXANDER, editors. 1987. Glossary of forest fire management terms. Fourth edition. National Research Council of Canada, Canadian Committee on Forest Fire Management, Ottawa, Ontario. Publication NRCC No. 26516. 91 p.

MCRAE, D.J. 1988. Forestry Canada, Great Lakes Forestry Centre. Personal communication.

An Evaluation of a 3-D Diagnostic Wind Flow Model (NUATMOS) with Implications for Its Use

B. H. CONNELL
Department of Natural Resource Management and Engineering
University of Connecticut, Storrs, Connecticut

D. G. FOX
G.L. WOOLDRIDGE
Rocky Mountain Forest and Range Experiment Station
Fort Collins, Colorado

Abstract

Data collected during the San Antonio Mountain Experiment (1980-1984) were used in the evaluation of the NUATMOS model. Three wind flow patterns classified by Froude number ($.15<Fr<.4$, $.7\ Fr<1$, $Fr>>1$) were modeled using sounding data as input. Modeled U and V wind components are compared with surface observations taken within the same timeframe as the sounding data. A total of ten model runs were made for each category. Results indicate that the best agreement between modeled and observed U and V wind components occur at the top of the mountain. Agreement between observed and predicted values was poor under low wind speeds and under conditions in which recirculating flow was observed in the lee side of the mountain.

Résumé

Les données recueillies lors de l'expérience du mont San Antonio (1980-1984) ont servi de données d'entrée lors de l'évaluation du modèle NUATMOS. Trois régimes d'écoulement du vent classés par nombre de Froude ($.15<Fr<.4$, $.7\ Fr<1$, $Fr>>1$) ont été modélisés à l'aide de données de sondage comme données d'entrée. Les sorties du modèle des composantes U et V du vent sont comparées aux observations en surface effectuées pendant la même période que le prélèvement des données de sondage. Un total de dix passages a été effectué pour chaque catégorie. Les résultats révèlent que c'est au sommet de la montagne que les composantes U et V modélisées et observées concordent le mieux. Les valeurs observées et prévues ne concordent pas lorsque la vitesse du vent est faible et lorsque le vent est recirculé du côté sous le vent de la montagne.

Introduction

Research efforts in meteorology over the last few decades have resulted in the development of numerical models to represent wind flow in complex terrain. Much of this effort has been directed towards applications in wind energy siting, recreation resource development, pest management, fire management, the control of air pollution and acid deposition resulting from mineral resource development, and other land use planning activities (Fosberg and Peterson 1986, Findlay 1982, Riebau et al. 1987).

Before a model can be used, its applicability and limitations must be evaluated. Venketram (1988) has described the basic steps in model evaluation as (1) examination of the structure of the model, (2) sensitivity analysis, and (3) testing of the model predictions against observations.

A diagnostic model, NUATMOS, developed by Ross et al. (1988) is evaluated here for Venketram's steps (2) and (3). In the evaluation, terrain and data from the San Antonio Mountain Experiment (McCutchan et al. 1982) are used as model input. The classification of three wind flow patterns based on the concept of the Froude number (Wooldridge et al. 1987) are modeled and evaluated quantitavely.

The Model

NUATMOS is a simple physically consistent 3-dimensional diagnostic model designed to minimize the difference between the initial interpolated wind field and the final wind field subject to a mass-consistent constraint. An existing model, ATMOS1, developed by Davis et al. (1984) was used as a framework in the development of NUATMOS.

The NUATMOS model employs terrain following coordinates and a variable vertical grid spacing to adequately represent complex terrain. Boundary conditions include no flow through the surface, and allow flow along the surface (free slip). Multi-grid techniques have been utilized to speed up numerical computations.

NUATMOS is capable of including atmospheric stability effects by the incorporation of a parameter (α) that controls the amount of adjustment made to the vertical wind component compared to the horizontal wind components during the divergence elimination phase. Ross et al. (1988) have proposed theoretical arguments based on the Froude number that relate α to atmospheric stability. The model is unable to

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

produce certain nonlinear phenomena without the incorporation of constraints to conserve momentum and/or the inclusion of actual surface and sounding data which depict the phenomena.

Froude Number Concepts

The Froude number has been used extensively to observe and characterize fluid flows in both stable and neutral environments. It has specifically been used to characterize air flow around isolated 3-dimensional obstacles (Lavery et al. 1982, Hunt and Snyder 1980, Wooldridge et al. 1987, Hosker and Barr 1980). The hill Froude number relates the inertia of the fluid to the buoyancy force that suppresses motion in the vertical and is defined:

$$Fr = U/Nh$$

where U is the characteristic upstream wind speed, h is the height of the hill, and N is the Brunt-Vaisala frequency

$$N = \sqrt{\frac{g}{\theta}\frac{\partial\theta}{\partial z}}$$

where g is the acceleration due to gravity, θ is the average potential temperature, and

$$\frac{\partial\theta}{\partial z}$$

is the potential temperature gradient.

Description of the Area and Experiment

San Antonio Mountain is located in north central New Mexico (36° 51' N lat., 106° 01' W long.) in the San Luis Valley. The mountain spans 10 km across its base and rises 670 m above the valley floor.

The San Antonio Mountain Experiment was conducted from September, 1980 to September, 1984. Nine surface weather stations recording wind speed and direction, among other variables, were located on the mountain to form NW-SE and NE-SW transects (Figure 1). A detailed description of the instruments used and resulting data base is provided in Connell et al. (1987).

Field studies involving the release and tracking of pilot balloons and superpressured mylar balloons with and without sondes attached were conducted during a 2-week period each year. Trajectories from the mylar balloons depicted boundary layer flow patterns, the pilot balloons provided profiles of atmospheric conditions and the weather stations provided surface conditions at the time.

As mentioned, Wooldridge et al. (1987) have calculated Froude numbers for the soundings, grouped the soundings based on Froude numbers, and developed mean flow patterns by normalizing trajectory data with respect to a mean westerly background wind. Actual sounding data from three of these wind flow patterns are used as input to the NUATMOS model and the model output is compared with surface observations. The following three paragraphs describe flow patterns developed by Wooldridge et al. (1987).

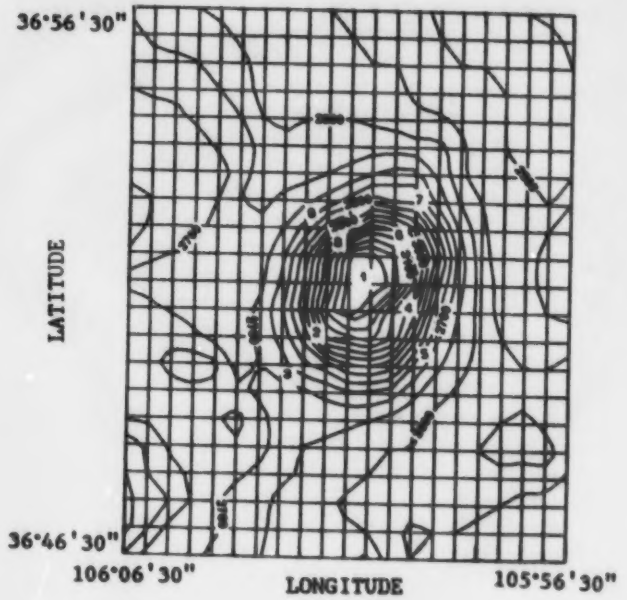


FIG 1. Horizontal grid domain and location of 9 surface weather stations imposed on the contour elevation map of the San Antonio Mountain (contour interval 50 m).

The first category represents stable atmospheric conditions (.15<*Fr*<.4) described by low wind speeds (.5 - 2 m/s) at the surface, a wind speed maximum between 300 and 400 m above the valley floor, and wind speeds increasing to 5-10 m/s at 2000 m above the surface. The surface wind flow pattern indicates air flowing horizontally around the moutain.

The second category represents an unstable layer with a stable layer above (.7<*Fr*<1.0). Surface wind speeds range from .5-5 m/s, wind speed maximums occur 300-400 m above the surface, and winds increase to 5-15 m/s at 2000 m above the surface. On the upwind side of the mountain, the air flow shows a combination of rising and horizontal movement. A rotor structure was observed in the lee side of the mountain centered near the base and extending 1500 m horizontally in diameter and 500 m vertically resulting in upslope flow on the lee side.

The third category represents unstable surface conditions with neutral conditions above ($Fr \rightarrow \infty$). Wind speeds average 5-10 m/s at the surface and increase to 10-20 m/s at 2000 m above the surface. The surface wind flow pattern depicts air rising on the upwind side, flowing over the top of the mountain, and descending down the lee side. Upper air trajectories depict a large rotor structure in the lee of the mountain (4000 m horizontal extent and 600 m vertical extent) extending up the back side of the mountain and away from the surface.

Model Evaluation

Venketram (1988) describes model evaluation as an evolutionary process of model improvement based on a comparison between predictions and observations. Expected deviations between model predictions and observations are often large. Four factors that contribute to these deviations are (1) error in model physics, (2) error in model inputs, (3) error in observations, and (4) inherent uncertainty caused by the natural random nature of the atmosphere. The difference between observed and predicted values is often used to quantify these various types of errors (Fox 1981). Correlation is also performed on the data to determine the measure of agreement between predictions and observations. The method used here to determine differences and measure of agreement between observed and predicted values falls into the recently developed class of permutation techniques termed multi-response permutation procedures (MRPP) (Mielke 1984). The specific method utilized here is based on a randomized block design.

This comparative evaluation involves g groups (or treatments), b blocks of the g groups, and r response measurements associated with each bg combination. Here, 2 blocks are defined (observed and model predicted values) with 2 different types of grouping (stations and model runs) and 2 responses (U and V wind components). The first type of grouping defines 9 groups associated with the 9 surface stations. Ten model runs from each Froude number category consisting of 9 groups of surface station data are compared with actual data producing 10 (x3) sets of output statistics.

The second type of grouping defines 10 groups associated with the 10 model runs and corresponding observational data. Nine stations within each Froude number category are evaluated separately, producing 9 (x3) sets of output statistics. The multi-response block permutation procedure (MRBP) statistic defined by Mieke (1984) is given by:

$$\delta = \left[g\binom{b}{2}\right]^{-1}\sum_{I=1}^{g}\sum_{j<k}\Delta\left(x_{Ij},y_{Ik}\right)$$

where Δ (x,y) is the symmetric distance function in the r-dimensional Euclidian space. The null hypothesis (H_0:$\delta_0 = \mu\delta$, where δ_0 is the realized value of δ and μδ is the mean of the distribution of δ) assigns equal probabilities to all possible permutations of the response measurements to the group positions within each of the blocks. In other words, the calculated δ represents the mean of the δ distribution function for a random sample of observed and predicted values. The symmetric distance function is defined as:

$$\Delta(x,y) = \left(\sum_{h=1}^{r}\left|x_h-y_h\right|^{p}\right)^{\frac{v}{p}}$$

with p=2, v=1 for this application (Euclidian space) (Mielke 1984).

Small values of δ imply a concentration of response measurements associated with each of the groups over the blocks. The probability value (P-value) based on a Pearson type III distribution associated with δ is therefore ($P\delta<\delta_0$) and a measure of agreement is defined as $\rho=1 - \delta/\mu\delta$ (Mielke 1984). A small P-value would indicate agreement between observed and predicted values. For the randomized block design, the P-value is computed by permuting the observations for each block among the groups, and hence, if the groups are diverse relative to similarity among blocks, a small probability value would likely result. The agreement measure supplies additional information on the difference between observed and predicted values since it reflects the null hypothesis. If the agreement measure is small relative to one, then the model is inadequately predicting the observations.

Results

A 21 x 21 grid with spacing of 30 seconds of latitude and longitude (743.5 m in the x direction and 929.2 m in the y direction) was used to define the horizontal model domain (Figure 1), with the vertical grid domain defined by 9 variably spaced layers. Vertical layers near the surface were closely spaced to adequately handle conditions associated with complex terrain, while layers above the surface were spaced progressively farther apart as the influence of the surface decreased.

Ten soundings from each Froude number category were used as input to the NUATMOS model to generate a total of 30 model runs. U and V wind components from the modeling grid were spatially interpolated to the location of the nine surface stations. These data were then compared with the actual surface station U and V wind component data. Actual vertical wind measurements were not available and therefore, no comparison with model output was possible.

The MRBP analysis was divided into three categories representing the three Froude number classes and the data were analyzed for two group regimes. The first regime consisted of analyzing the 9 station groups for individual runs. The second regime consisted of analyzing the 10 model run groups for each station.

The results of the analysis are represented in Tables 1 and 2. Comparing probability values and agreement measures from the first regime by individual model runs (Table 1) suggests no model run did exceptionally

Table 1. Computed values of the MRBP statistic (δ), the mean of the distribution of δ (uδ), probability values (P) and agreement measures (ρ) for comparison of station observations with model predictions for the 3 Froude categories. Each run analyzed for 9 station groups.

Category		Model Runs									
		1	2	3	4	5	6	7	8	9	10
1	δ	1.861	2.369	1.488	1.203	1,478	1.771	1,474	0.864	1.853	1.472
	μδ	2.021	2.827	1.766	1.356	1.442	1.803	1.569	1.371	1.972	1.788
	P	.100	.032	.010	.052	.775	.357	.288	.002	.194	.027
	ρ	.079	.162	.158	.113	-.243	.018	.061	.370	.061	.177
2	δ	3.351	3.665	4.993	3.590	2.633	2.161	4.800	4.414	2.624	6.183
	μδ	3.712	3.730	5.585	3.989	3.375	2.787	5.126	4.872	3.211	6.259
	P	.077	.380	.006	.004	.008	.006	.087	.018	.017	.356
	ρ	.097	.017	.106	.100	.220	.225	.064	.094	.183	.012
3	δ	3.102	2.651	6.635	6.697	6.562	3.774	5.444	2.544	8.813	5.441
	μδ	3.137	2.901	7.050	7.061	6.865	3.912	5.458	2.793	9.337	5.582
	P	.240	.105	.012	.046	.125	.086	.470	.100	.210	.242
	ρ	.011	.086	.059	.052	.044	.035	.002	.089	.056	.025

Table 2. Computed values of the MRBP statistic (δ), the mean of the distribution of δ (μδ), probability values (P) and agreement measures (ρ) for comparison of station observations with model predictions for the 3 Froude categories. Each station analyzed for 10 model run groups.

Category		Stations								
		1	2	3	4	5	6	7	8	9
1	δ	1.338	1.628	1.585		2.106	1.379	1.286	1.812	1.325
	μδ	1.991	2.003	1.905		2.322	1.435	1.659	2.105	1.621
	P	.006	.065	.049		.081	.355	.017	.077	.027
	ρ	.328	.187	.168		.093	.039	.225	.139	.183
2	δ	2.750	2.556	2.008	4.911	4.144	3.310	5.420	4.221	4.730
	μδ	4.551	4.028	3.558	5.865	4.764	4.331	5.897	3.784	4.169
	P	.002	.006	.005	.006	.013	.033	.128	.867	.974
	ρ	.396	.365	.436	.163	.130	.236	.081	-.115	-.135
3	δ	3.177	3.230	7.283	9.502	4.423	4.823	5.095	3.846	4.570
	μδ	7.023	5.025	7.882	9.486	6.982	7.064	8.206	6.907	7.177
	P	.0002	.002	.221	.505	.006	.002	.001	.004	.009
	ρ	.547	.357	.076	-.002	.336	.317	.379	.443	.363

well for any Froude category in predicting observed values. The increase in the MRBP distribution function (δ) and corresponding increase in the mean (μδ) over the categories seem to be related to the increase in wind speeds for each category.

The best model run for Froude category 1 (run 8) had a low P-value of .002 and an agreement measure of .37. Interpretation of the P-value would lead to a rejection of the null hypothesis at a 1% level of significance; stated differently, the calculated distance function is small, indicating little difference between observed and predicted U and V wind components. However, as discussed previously, a small P-value could also indicate that the groups (the 9 stations) are diverse relative to similarity among blocks (observed vs. predicted values). There is some indication of this possibility reflected in the low measure of agreement (ρ=.37) relative to one.

The modeled surface horizontal streamline windflow representation characteristic of this group is shown in Figure 2. The wind field is characterized by low surface wind speeds. Ross and Smith (1987) identify a critical wind speed of 2 m/s below which correlations between observed and predicted values are poor and interpolation of observations become unreliable. They suggest that diagnostic wind models are inadequate for defining wind flow at low wind speeds. Under low wind speeds, local effects may predominate and surface measurements may not be adequate to represent these effects, hence the model is unable to preserve these features.

In category 2 ($0.7<Fr<1.0$), runs 5 and 6 are the best runs, although for low P-values, there are also low ρ values. Overall there is poor agreement between model predictions and actual observations. Greater disagreement is expected for this Froude category than the previous one. Actual trajectories of superpressured mylar balloons indicate a rotor structure in the lee of the mountain (Wooldridge et al. 1987). This sort of physical phenomenon cannot be generated by the model and will only be preserved by the model if the phenomenon is represented in the input.

The surface horizontal streamline windflow representation of this category is similar to that for category 1 (Figure 2) and shows no indication of circulation in the lee side of the mountain. In the analysis here, the wind field was generated using a single upwind sounding. This has proven inadequate in representing the wind flow pattern, hence there are expected differences between observed and predicted values.

Results from model runs for the third category ($Fr\rightarrow\infty$) show that the model poorly predicts actual observations. Higher P-values than for the other two categories and low agreement measures suggest significant differences between observed and predicted values. From observations of Wooldridge et al. (1987) the surface representation of the flow indicates air movement up and over the mountain, with the trajectory data indicating an extensive rotor structure in the leeside of the mountain away from the surface. Although the modeled surface horizontal streamline wind field does depict the surface flow (Figure 3), the lee side rotor possibly exerts some other influence on the surface station measurements that is not accounted

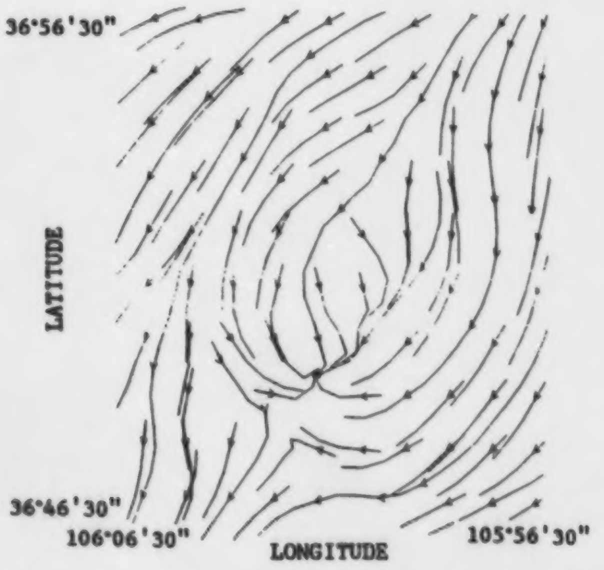


FIG 2. Modeled surface streamline wind representation characteristic of category 1.

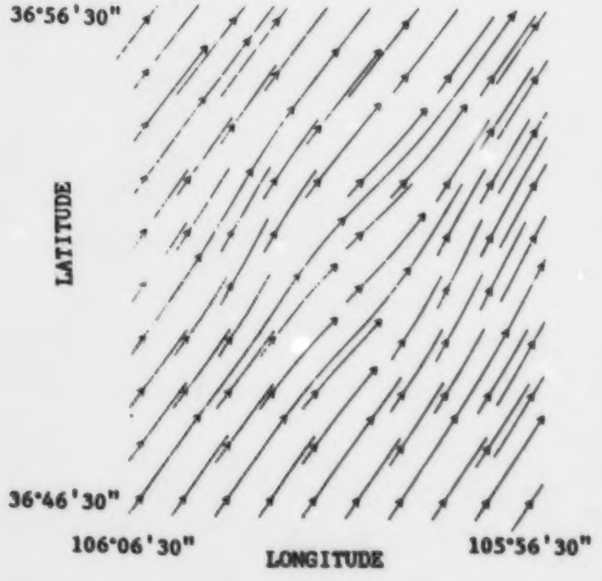


FIG 3. Modeled surface streamline wind representation characteristic of category 3.

or in the model, and hence results in differences between observed and predicted wind values.

Results from the second regime consisting of analysis for 10 model run groups for each station (Table 2) presents another view of what is occurring between model predictions and observations. Overall, station 1 at the summit of the mountain shows the best agreement between observed and predicted values.

Category 1, which was characterized by low input wind speeds and input wind directions from almost all aspects of the compass, was poorly represented by the model. Category 2 had moderate input wind speeds and a narrower range of input wind directions (predominately southwesterly). In this case, the better predicted observations from stations 1-3 were located in the upwind area of the mountain. The poorly predicted observations from stations 7-9 were located in the lee area of the mountain.

Input data for category 3 were characterized mainly by high wind speeds and southwesterly winds, and resulted in low P-values and higher ρ values than in the other categories. The higher agreement for stations in this category reflects to some extent the high input wind speeds; the influence of the higher winds overrides local effects. As shown in the previous group analysis, however, an individual model run is poorly predicted.

The analysis shows that stable conditions are poorly represented for low wind speeds. The other atmospheric conditions are poorly represented in part due to the model's inability to generate recirculating flow in the lee side of the mountain. The next step to represent flow patterns described by groups 2 and 3 would be to gather surface and sounding data, normalize them with respect to direction, and use these data as input to the model.

Utilizing the flow visualization data developed by Wooldridge et al. (1987), simulated soundings for category 2 were prepared and input to the model. The resulting wind flow pattern near the surface and a W-E cross section of vertical velocity are depicted in Figures 4 and 5. The output presents a suitable representation of observations noted in the field, showing that the model will preserve a physical phenomena input to it.

Summary and Conclusion

Data from the San Antonio Mountain Experiment were used to evaluate the NUATMOS model. Thirty soundings from three Froude number categories ($.15<Fr<.4$, $.7<Fr$ 1, $Fr\rightarrow\infty$) were used as model input. Output was compared with actual data from the nine surface stations located on the mountain.

Low wind speeds contributed to poor agreement between observed and predicted U and V wind components in the first category ($Fr<.4$). Although the third category showed the best agreement between observed and predicted values for each station, overall results suggested poor prediction of observations. The

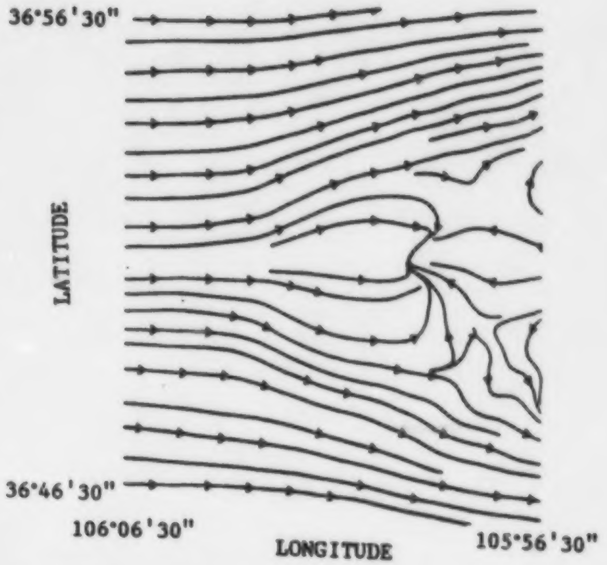


FIG 4. Modeled surface streamline wind representation for category 2 using composited data as input.

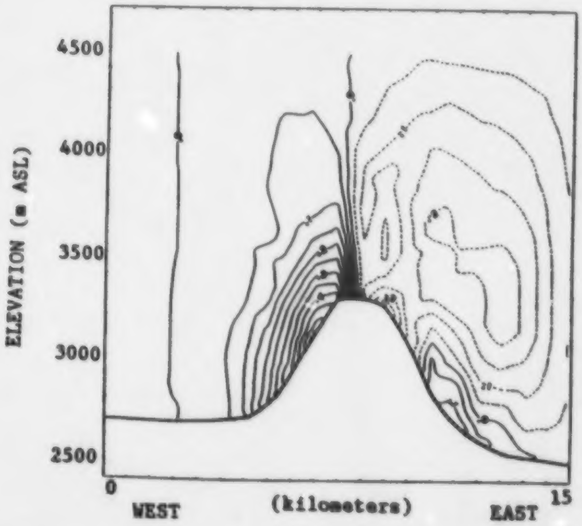


FIG 5. Modeled W-E cross section of vertical velocity contours for category 2 using composited data as input (contour interval .1 m/s; solid lines denote positive values, dashed lines denote negative values).

poor predictions reflect the model's inability to generate observed recirculating flow in the lee side of the mountain. The overall results suggest that one input sounding is inadequate to represent complex wind flows.

A realistic representation of the flow pattern for category 2 ($.7<Fr<1.0$), generated using composite data from Wooldridge et al. (1987) as input, suggests an extension of the use of the model. Because the model is relatively simple to run, its use to predict winds in emergency situations would be desirable. Future use and development should incorporate further evaluation against actual observations. This particular evaluation has pointed out the importance of upper air observations to supplement surface observations in determining wind flow patterns.

Acknowledgements

The authors wish to thank Rudy King for his comments on the interpretation of the statistics used in this paper.

References

CONNELL, B.H., D.G. FOX, and G.L. WOOLDRIDGE. 1987. San Antonio Mountain Experiment (SAMEX) data base. P. 158-164. In Proc. Ninth Conf. Fire and For. Meteor., San Diego, Ca., Apr. 21-24, 1987, Amer. Meteor. Soc., Boston, Ma.

DAVIS, C.G., S.H. BUNKER, and J.P. MUTSCHLEENER. 1984. Atmospheric transport models for complex terrain. J. Clim. Appl. Meteor. 23(2):235-238.

FINDLAY, B.F. 1982. Applications of meteorology to land use planning. WMO Report for the Commission for Climatology and Applications.

FOSBERG, M.A., and M. PETERSON. 1986. Modeling airborne transport of gypsy moth (Lepidoptera: Lymantriidae) larvae. Ag. and For. Meteor. 38(1-3):1-8.

HOSKER, R.P., and S. BAR. 1980. Using laboratory flow models to simulate terrain-influenced meteorology. In M.H. Dickerson, ed., ASCOT Information Survey, UCID-18572, ASCOT-80-3, May.

HUNT, J.C.R. and W.H. SNYDER. 1980. Experiments on stably and neutrally stratified flow over a model three-dimensional hill. J. Fluid Mech. 96(4):671-704.

LAVERY, T.F., A. BASS, D.G. STRIMAITIS, A. VENKETRAM, B.R. GREEN, P.J. DRIVAS, and B.A. EGAN. 1982. EPA complex terrain model development first milestone report - 1981, EPA 600/3-82-036.

MCCUTCHAN, M.H., D.G. FOX, and R.W. FURMAN. 1982. San Antonio Mountain Experiment (SAMEX). Bull. Amer. Meteor. Soc. 63:1123-1131.

MIELKE, P.W. 1984. Meteorological applications of permutation techniques based on distance functions. P. 813-830. In P.R. Krishnaiah, and P.K. Sen, eds., Handbook of Statistics, Vol. 4, Elsevier Science Publishers.

RIEBAU, A., D.G. FOX, and W.E. MARLATT. 1987. TAPAS: Topographic air pollution analysis system. Bureau Land Mgt. Tech. Note 375, May.

ROSS, D.G., and I.N. SMITH. 1987. Diagnostic wind field modelling: development and validation. Centre Appl. Math. Modelling Report No. 5/87 Feb., Chisholm Inst. Techn.

ROSS, D.G., I.N. SMITH, P.C. MANINS, and D.G. FOX. 1988. Diagnostic wind field modeling for complex terrain: model development and testing. J. Clim. Appl Meteor.

VENKETRAM, A. 1988. Topics in applied dispersion modeling. P. 308-324. In A. Venketram, and J.C. Wyngaard, eds., Lectures on Air Pollution Modeling. Amer. Meteor. Soc., Boston, Ma.

WOOLDRIDGE, G.L., D.G. FOX and W.R. FURMAN. 1987. Airflow patterns over and around a large three-dimensional hill. Meteor. Atmos. Phys. 37:259-270.

An Extensive Blowdown Occurrence in Northwestern Ontario[1]

M.D. FLANNIGAN
Forestry Canada
Petawawa National Forestry Institute
Chalk River, Ontario

T.J. LYNHAM
Forestry Canada
Great Lakes Forestry Centre, Ontario Region
Sault Ste. Marie, Ontario

P.C. WARD
Ontario Ministry of National Resources
Aviation and Fire Management Centre
Sault Ste. Marie, Ontario

Abstract

Severe surface winds were experienced in eastern Manitoba and northwestern Ontario in the evening and overnight on June 24-25, 1988. Four general areas of forest blowdown occurred in northwestern Ontario. Within each general area, contiguous areas of blowdown ranging from a few hectares to over a thousand hectares were observed. Isolated occurrences of private property damage were reported, but the main areas of blowdown were sparsely populated.

The cause of the severe surface winds was investigated using meteorological data from the period June 23-26, 1988. It was found that a vigorous cold front, associated with a fast moving low pressure system, provided the mechanism for higher wind speeds aloft to reach the surface. The high wind speeds aloft were associated with an upper level jet stream over the region.

These blowdown areas are of serious concern to fire managers in the region. Very heavy coniferous fuel loadings were concentrated on the blowdown sites, with a large proportion of fine aerial fuels. As the downed material cures, an increasing amount will be available for combustion. The fuel arrangement will also hamper conventional ground attack should a fire occur. A similar, but more extensive blowdown occurred in the same region in 1973 and was followed by a wildfire in 1974 that burned 32,000 hectares of blowdown fuel.

Résumé

Dans la soirée du 24 juin 1988 et la nuit du 24 et 25, de violents vents de surface ont sévi dans l'est du Manitoba et le nord-ouest de l'Ontario. Dans cette dernière région, il y a eu quatre zones générales d'abattage d'arbres par le vent. Dans chacune des régions générales, on a observé des zones contigués d'abattage par le vent, allant de quelques hectares à plus de 1 000 hectares. On a signalé des cas isolés de dégâts aux biens privés, mais, heureusement, les principales zones d'abattage par le vent n'étaient que peu peuplées.

On a étudié la cause des vents violents de surface, en utilisant les données météorologiques disponibles de la période allant du 23 au 26 juin 1988. On a constaté qu'un front froid vigoureux, lié au système de basse pression à déplacement rapide, a fourni le mécanisme suivant lequel des vents de vitesse élevées, en altitude, sont parvenus à la surface. Ces vents étaient liés à un courant-jet de haute altitude qui soufflait au-dessus de la région.

Ces zones d'abattage préoccupent beaucoup les responsables de la lutte contre l'incendie de la région. De très fortes charges de combustibles de conifères sont concentrées dans les lieux d'abattage, ainsi qu'une grande proportion de fins combustibles aériens légers. Quand les matériaux abattus seront secs, il y aura une quantité d'autant plus importante disponible pour la combustion. La disposition des combustibles rendra aussi très difficile la lutte classique, au sol si un, incendie avait lieu. Un cas analogue de vaste abattage par le vent, survenu dans la même région en 1973, fut suivi, en 1974, par un feu de friches qui a brûlé 32,000 hectares de combustibles en majeure partie abattus par le vent.

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

Introduction

During the evening of June 24 and the early morning of June 25, 1988, strong surface winds resulted in areas of extensive blowdown over northwestern Ontario. Blowdown occurred in the Dryden, Sioux Lookout, and Ignace Districts (Figure 1). The blowdown area totals 21 000 ha and includes 13 000 ha of wind damaged forests in the Dryden and Sioux Lookout Districts with an additional 8 000 ha in the Ignace District (House and Applejohn 1988). Figure 2 shows three prominent pockets of blowdown, connected by many smaller areas of damage, that give rise to a 90 km band of damage that runs southeast from Anishinabi Lake, south of Lac Suel, and then continuing southeast. The path of damage reappears about 70 km farther southeast, at the north end of Ignace District.

The purpose of our study was threefold: i) to investigate the cause of the extensive blowdown, ii) to demonstrate a mapping methodology that readily depicts this scale of forest damage, and iii) to consider the impact of the blowdown areas on fire management.

The region of northwestern Ontario where the blowdown was observed is part of the Boreal Forest Region of Ontario (Rowe 1972). The forest is primarily composed of jack pine (Pinus banksiana Lamb.), black spruce (Picea mariana (Mill.) B.S.P.) with mixtures of white spruce (Picea glauca (Moench) Voss), balsam fir (Abies balsamea (L.) Mill.), trembling aspen (Populus tremuloides Michx.), and white birch (Betula papyrifera Marsh.) (Rowe 1972). The mosaic of patterns in this forest are the result of a disturbance regime, primarily fire, but wind also plays an important role. This part of the boreal forest is on a portion of the Canadian Shield with a rough, rolling topography although relief is not great. The region has shallow soils with many lakes and rock outcrops. The region has a continental climate with a mean annual precipitation of 600-700 mm (Atmospheric Environment Service 1982) and a mean annual temperature of 1.5°C (Atmospheric Environment Service 1982).

The occurrence of blowdown in the forest is not a rare event. Blowdown results from strong surface winds generated by a variety of processes ranging from tornadoes, thunderstorms, hurricanes, and synoptic scale features like cold fronts. Tornadoes occur approximately at a rate of 0.4 to 0.8 per 10^4km^2 per year in this part of Ontario (Newark 1983). This results in a probability of tornado damage of about .02% annually which is 1/10 of the area burned by forest fires each year in Ontario (Harrington and Donnelly 1978). Harrington and Newark (1986) detailed the interaction of a tornado with rough terrain and its associated forest cover. Foster (1988 a,b) described how catastrophic windstorms have played an integral part in the diversity of the temperature forest. Wind speeds of 90-125 km/h (25-35 m/s) occur every 5-10 years in northwestern Minnesota (Simiu et al. 1979, 1980, Baker 1983), just south of our region of interest. Similar statistics could be assumed for northwestern Ontario, with blowdown being a fairly regular event. This is particularly true when considering the shallow soils common to this area, which suggests a greater frequency of blowdown.

Extensive blowdown did occur in 1973 in the same general area when 40 000 ha of standing timber were severely wind damaged (Stocks 1975). The interesting aspect of that event was that 32 000 ha of the blowdown area burned in a lightning-caused wildfire the following year. This aspect of susceptibility to fire and the associated fire management problem will be presented after the discussion of the weather conditions associated with the 1988 blowdown.

Weather Conditions Associated with the Blowdown Event

The blowdown took place during the evening of June 24 and the early hours of June 25, 1988. Meteorological data for the period June 23-26, 1988 were obtained from the Atmospheric Environment Service of Canada. This data included upper air analyses from 250, 500, 700, 850 hPa, surface analyses, tephigrams from Churchill, The Pas, Trout Lake, and International Falls (see Figure 1), and hourly weather observations from stations in Northwestern Ontario, eastern Manitoba and northern Minnesota. Detailed examination of the meteorological data was undertaken to discover how and why this disturbance occurred.

Upper air analyses show a west-to-east jet stream (250 hPa level) with wind speeds in excess of 180 km/h moving directly over the blowdown area during the period (June 24, 1800 CDT - June 25, 0600 CDT). The 500 hPa analysis (Figure 3) at 1800 CDT June 24, 1988 depicts a strong zonal flow over southern sections of northwestern Ontario, with a significant shortwave trough moving through Manitoba. A slowly deepening surface low pressure system associated with the upper air trough moved rapidly eastward (Figures 4-6) across our region during the time of interest. A warm front extended from the low southeastward and a cold front from the low southeastward. In the warm sector, the airmass was hot, moist, and unstable, with temperatures above 30°C and dewpoints as high as 22°C. Thunderstorms were associated along the cold and warm fronts. Vigorous thunderstorms developed near the frontal wave at the center of the surface low by June 24 1800 CDT. A tornado was reported at Gimli, Manitoba at 1849 CDT June 24. Strong gusty winds from the northwest were reported along the cold front, with speeds of up to 120 km/h.

Two separate mechanisms may have been responsible for the strong surface winds associated with this system:

1) severe thunderstorms including tornadoes, and
2) a lobe of high wind speeds extending down from the upper level jet stream to the earth's surface.

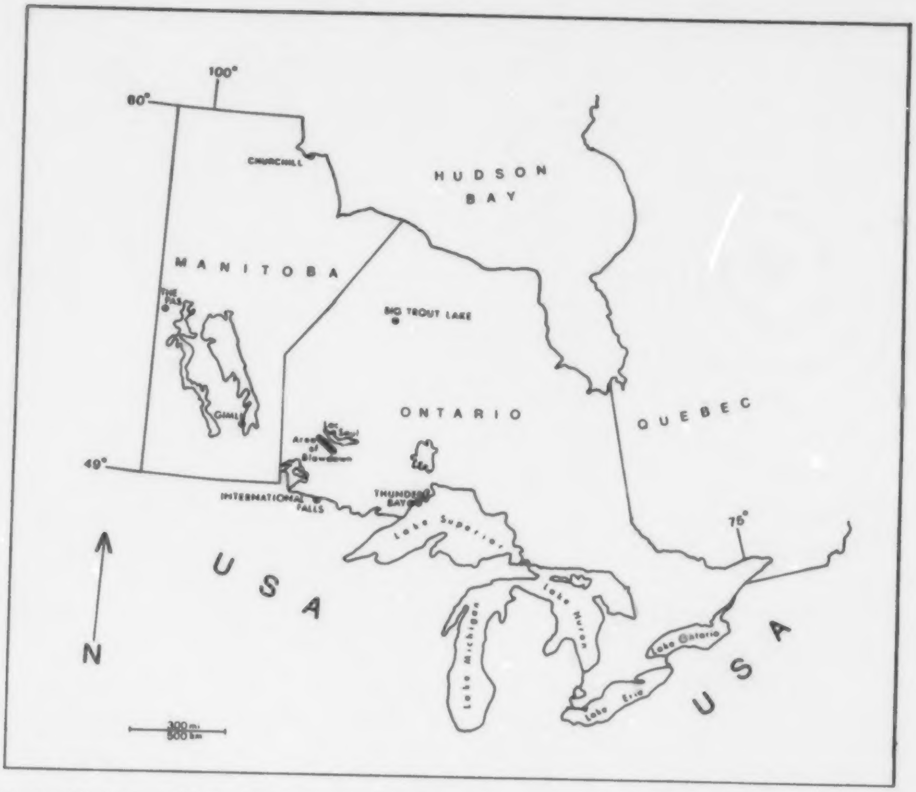

100°
60°
CHURCHILL
HUDSON BAY
MANITOBA
THE PAS
BIG TROUT LAKE
GIMLI
ONTARIO
QUEBEC
Lac Seul
Area of Blowdown
49°
INTERNATIONAL FALLS
THUNDER BAY
Lake Superior
75°
USA
N
Lake Michigan
Lake Huron
Lake Ontario
Lake Erie
USA
300 mi
500 km

FIG 1. Ontario Ministry of Natural Resources Districts of northwestern Ontario where the blowdown occurred.

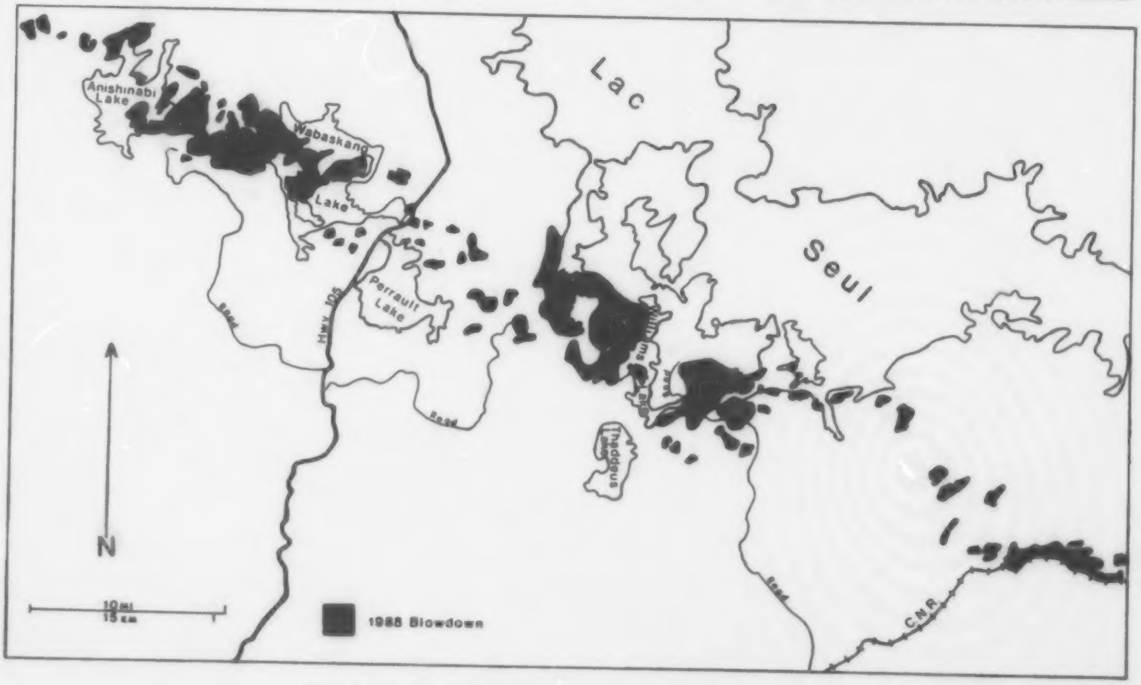

Lac Seul
Anishinabi Lake
Wabaskang Lake
Perrault Lake
Hwy 105
Road
Road
Thaddeus Lake
Road
N
10 mi
15 km
1988 Blowdown
Road
CNR

FIG 2. Areas of blowdown over northwest Ontario.

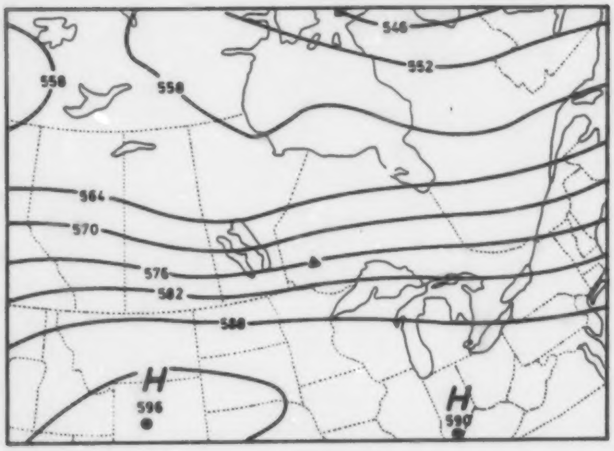

546
552
558
558
564
570
576
582
588
H
596
H
590

FIG. 3. The 500 hPa analysis at 1800 CDT June 24, 1988. Contour heights are in decameters drawn at intervals of 60 m. The general area of blowdown is indicated by the '▲'.

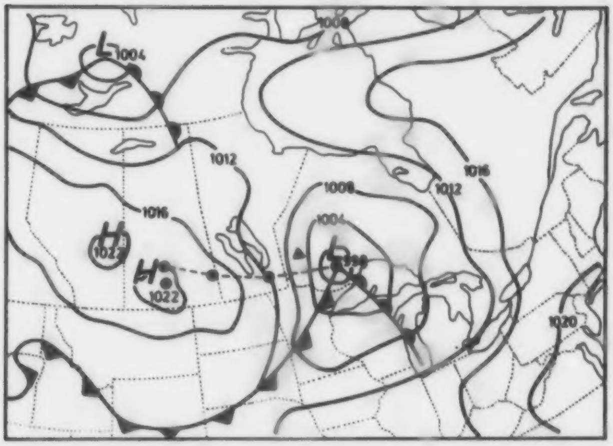

L
1004
1008
1012
1016
1012
1016
1008
1004
H
1022
H
1022
L
1020

FIG. 5. Surface pressure analysis at 0000 CDT June 25, 1988.

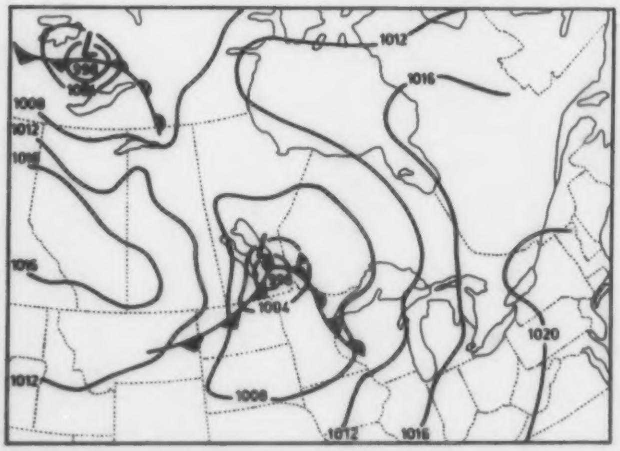

L
1012
1016
1008
1012
1016
1016
1004
1020
1012
1008
1012
1016

FIG. 4. Surface pressure analysis at 1800 CDT June 24, 1988. Isobars are drawn at intervals of 4 hPa.

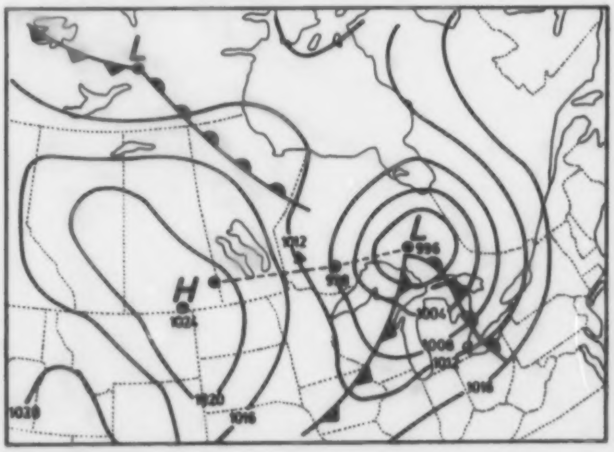

L
1012
H
1024
L
996
1000
1004
1008
1012
1016
1020
1016
1030

FIG. 6. Surface pressure analysis at 0600 CDT June 25, 1988.

The first mechanism is well known; the second is somewhat obscure. Strong winds are associated with severe thunderstorms and tornadoes. These winds can result in blowdown of forested areas. Strong surface winds associated with the upper level jet stream have been documented. Flannigan and Harrington (1987) found that a coupling of the surface wind with a jet stream aloft through the action of strong thermal convection generated strong surface winds. Stocks and Flannigan (1987) found that strong surface winds that resulted in a major run of an Ontario wildfire (Red Lake #7/86) were associated with an upper level jet stream overhead. Figure 7 shows the vertical wind profile and hodograph* for the radiosonde at International Falls at 0600 CDT June 25, 1988. The strongest winds passed to the north of International Falls some 3 to 6 hours prior to the ascent at 0600 CDT. However, from this figure we see strong winds extending from the jet stream down to within a few thousand metres of the surface. Note also that the wind direction at all levels is nearly the same -- northwesterly.

Strong surface winds were responsible for forest damage along a 160 km corridor. Large scale forest change like this blowdown event can be effectively monitored using satellite imagery which is the subject of the next section.

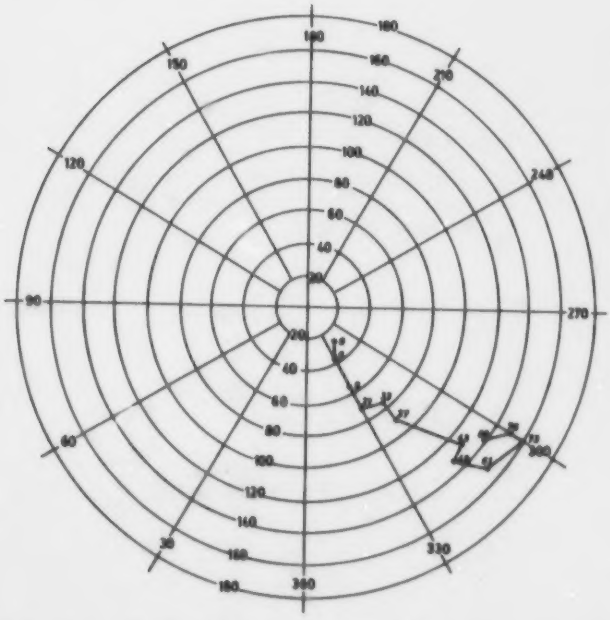


FIG. 7. Vertical wind profile and hodograph for International Falls, Minnesota for 0600 CDT June 25, 1988. Wind speed is indicated by the concentric circles in km/h. Wind direction is in degrees. The height is indicated in hundreds of meters by the number beside each data point.

Mapping Methodology

The intent in mapping the blowdown area was to demonstrate a reliable methodology for mapping large scale forest change, as well as providing fire managers with a comprehensive product that could provide some information on the extent of the 1988 blowdown. Banner and Lynham (1981) reported on an effective method for mapping forest depletion resulting from forest cutovers using two Landsat Multi-Spectral Scanner (MSS) images of the same area. Images were taken before and after the occurrence of forest cutovers. By combining band 5** (0.6 to 0.7 um) data from both images they were able to produce a colour composite that depicted the areas of change as red. A similar procedure was chosen to map areas of the 1988 blowdown in northwestern Ontario.

Landsat MSS data from June 11, 1984 was selected to represent the forest area before the blowdown event on June 24, 1988. For post-blowdown imagery, Landsat MSS data for June 30, 1988 was available. Both images were geometrically corrected on an Aries II image analysis system (at the Ontario Centre for Remote Sensing, Toronto, Ontario) to be compatible with National Topographic System (NTS) maps. A colour composite was created on a colour monitor by taking band 5 data from June 11 and assigning it to both the blue and green guns of the monitor, while the band 5 data from June 30 was added to the picture using the red gun. With band 5 Landsat data, bare ground appears much brighter than the surrounding forest. Because only the post-blowdown image had bright patches due to the blowdown, the patches showed red in the colour composite. The rest of the surrounding forest appeared in gray tones.

Although this technique causes area of blowdown to appear red on a colour composite, any other areas of change (e.g., cutovers or roads) also appear red. The areas of blowdown were identified on the basis that the reflectance from them was unique (i.e., they had lower reflectance values than the cutovers or roads), resulting in a darker red than for other types of forest change. Verification of blowdown areas was achieved by using the aerial reconnaissance mapping completed by the Forest Insect and Disease Survey, Forestry Canada, Ontario Region (House and Applejohn 1988; see figure 1). In addition, sketch maps and video tape, produced by the authors (taken in July 1988) and the Ontario Ministry of Natural Resources, were used to confirm the mapped areas of blowdown.

Discussion

The analysis of information leads us to believe that the blowdown was the result of strong winds from the lower extremity of an upper level jet stream being mixed down to the surface. Severe thunderstorms werepresent near the vicinity of the wave but the pattern of the blowdown trees is not typical of a thunderstorm event. That is, the trees blown down were all pointing along the same axis, northwest to southeast, except one small region near Hudson. The path of damage was also oriented in a northwest-southeast orientation. Surface weather stations in Manitoba observed winds around 100 km/h along and behind the cold front, with no thunderstorm activity present. The authors flew over the blowdown area, and one section near Hudson had a pattern of toppled trees that may have been the result of a severe thunderstorm or a tornado. However, the topography in this region is rugged so the pattern of toppled trees could have been due to the interaction of strong winds with rough terrain. Unfortunately, we have not found any eye witnesses who can confirm the possibility that strong winds responsible for the blowdown were associated with thunderstorms. However, additional information including radar and lightning data is being gathered to verify our hypothesis.

---

*A Hodograph is a graph of wind speed and direction as a function of height.

**Lansat Band 5 closely resembles black and white panchromatic film.

Strong northwest surface winds were associated with strong winds aloft being mixed down to the surface. This mixing was achieved by the action of the cold front and by instability during and after passage of the cold front. Blowdown occurred in exposed areas on hills and ridges. Trees were uprooted as well as snapped. Webb (1988) shows that snapping and uprooting are a function of tree size and not tree species, with the larger trees being snapped.

These blowdown areas are of serious concern to fire managers. A similar blowdown event in 1973 was followed by a large wildfire in 1974. McRae (1980) reported pre-burn fuel loads for small and medium slash pieces (0-6.99 cm in diameter) of 2.5 to 4.4 kg/m^2 for jack pine and lowland black spruce sites that were logged conventionally[5] versus fuel loads of 3.0 kg/m^2 for balsam fir stands where the standing forest was tramped. The same report indicates pre-burn fuel loads for heavy slash fuels (7.0 cm in diameter or greater) of 5.6 to 7.3 kg/m^2 for jack pine and lowland black spruce sites that were logged conventionally versus fuel loads of 18 kg/m^2 for the tramped balsam fir stands. Blowdown areas will have similar fuel loads, in the fine and medium slash size classes, as sites that have been logged conventionally; however, blowdown areas will have much greater fuel loads in the heavy size classes than conventionally logged cutover sites.

Reducing fuel loads is a difficult task. Salvage operations would be difficult because of lack of access, obstructions from the downed timber, and snapped, cracked, or twisted boles. Prescribed fire would be hard to contain with such heavy fuel loads. The fuel continuity and the amount of fuel would intensify fire behaviour and impede conventional ground attack, possibly resulting in an uncontrollable wildfire. However, the Alberta Forest Service[6] has successfully reduced fuel loads in blowdown areas by burning on days with lower indices of the Canadian Forest Fire Weather Index System (Canadian Forestry Service 1984, Van Wagner and Pickett 1985, Van Wagner 1987). By burning during lower indices the threat of an escaped fire is reduced.

The susceptibility of blowdown areas to fire ignition, as compared to the standing forest, is unknown. Lightning risk is random across northwestern Ontario. There is little expectation of human-caused ignition due to the lack of access to most of the blowdown. The exception is the area west of Hudson where the blowdown cut across a logging road.

Summary

Strong surface winds, associated with thunderstorms and the lower extremity of an upper level jet stream being mixed to surface, resulted in 21 000 ha of forest blowdown. Blowdown events are fairly common and constitute a significant portion of forest disturbance.

Blowdown areas are a concern to fire managers. Their large and complex fuel loads makes fires difficult to control. The potential for extreme fire behaviours exists given the high fuel loads and severe fire weather. Little can be done to alleviate the current situation from a fire control viewpoint. However, fire managers should be aware of the potential problems and should carefully monitor blowdown areas during the fire season.

Acknowledgements

The authors wish to thank Dennis Larmand and staff of the Ontario Ministry of Natural Resources, Northwestern Region for providing transportation and other assistance during field examination of the blowdown area.

Our appreciation is extended also to Dr. S. Pala, D. White, and staff of the Ontario Centre for Remote Sensing (Ministry of Natural Resources) for the use of the Centre's facilities and for their guidance during Landsat image analysis.

[5] In the process of conventional logging, trees are topped and delimbed where they are felled and the log is skidded to a roadside landing.

[6] Personal communication, Terry Van Nest, Alberta Forest Service.

References

ATMOSPHERIC ENVIRONMENT SERVICE. 1982. Canadian Climate Normals. Volume 2. Temperature 1951-80.

ATMOSPHERIC ENVIRONMENT SERVICE. 1982. Canadian Climate Normals. Volume 3. Precipitation 1951-80.

BAKER, D.G. 1983. Climate of Minnesota. Part XIV. Wind climatology and wind power. Univ. Minn. Agric. Exp. Stn. Tech. Bull. AD-TB1955.

BANNER, A.V., AND T.J. LYNHAM. 1981. Multitemporal analysis of Landsat data for forest cutover mapping. Pages

233-240 In Seventh Symp. Remote Sensing, Winnipeg, Manitoba.

CANADIAN FORESTRY SERVICE. 1984. Tables for the Canadian Forest Fire Weather Index System. Fourth ed. Environ. Can., Can. For. Serv., Ottawa, Ont. For. Tech. Rep. 25.

FLANNIGAN, M.D., AND J.B. HARRINGTON. 1987. Synoptic Weather Conditions During the Porter Lake Experimental Fire Project. Climatol. Bull. 21:19-40.

FOSTER, D.R. 1988a. Disturbance History, Community Organization and Vegetation Dynamics of the Old-Growth Pisgay Forest, south-western New Hampshire, U.S.A. J. Ecol. 76:105-134.

FOSTER. D.R. 1988b. Species and Stand Response to Catastrophic Wind in Central New England, U.S.A. J. Ecol. 76:135-151.

HARRINGTON, J.B., AND R. DONNELLY. 1978. Fire probabilities in Ontario's boreal forest. Pages 1-4 In Preprint vol. Fifth Joint Conference on Fire and Forest Meteorology. Amer. Met. Soc., Boston.

HARRINGTON, J.B., AND M.J. NEWARK. 1986. The Interaction of a Tornado with Rough Terrain. Weather 41:310-318.

HOUSE, G.M., AND M.J. APPLEJOHN. 1988. Survey Bulletin: Forest Insect and Disease Conditions in Ontario. Can. For. Serv., Sault Ste. Marie, Ontario. Fall Issue.

MCRAE, D.J. 1980. Preliminary fuel consumption guidelines for prescribed burning in Ontario slash fuel complexes. Can. For. Serv. Inf. Rep. O-X-316.

NEWARK, M.J. 1983. Tornadoes in Canada for the Period 1950 to 1979. CLI 2-83, Atmospheric Environment Service, Toronto.

ROWE, J.S. 1972. Forest Regions of Canada. Can. For. Serv. Publication No. 1300. Ottawa.

SIMIU, E., M.J. CHANGERY, AND J.J. FILLIBEN. 1979. Extreme windspeeds at 129 stations in the contiguous United States. NBS Build. Sci. Ser. U.S. No. 118.

SIMIU, E. 1980. Extreme windspeeds at 129 Airport Stations. J. Struct. Div. Am. Soc. Civil. Eng. 106:809-817.

STOCKS, B.J. 1975. The 1974 wildfire situation in northwestern Ontario. Can. For. Serv., Sault Ste. Marie, Ont. Report O-X-232.

STOCKS, B.J., AND M.D. FLANNIGAN. 1987. Analysis of the Behaviour and Associated Weather for a 1986 Northwestern Ontario Wildfire: Red Lake No. 7. Pages 94-100 In Ninth Conf. on Fire and Forest Meteorol., San Diego, Ca. April 21-24, 1987. Am. Meteorol. Soc.

VAN WAGNER, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Can. For. Serv., For. Tech. Rep. 35.

VAN WAGNER, C.E., AND T.L. PICKETT. 1985. Equations and FORTRAN program for the Canadian Forest Fire Weather Index System. Can. For. Serv., For. Tech. Rep. 33.

WEBB, S.L. 1988. Windstorm damage and microsite colonization in two Minnestoa forests. Can. J. For. Res. 18:1186-1195.

The California Lightning Fires of 1987

F.M. FUJIOKA
Pacific Southwest Forest and Range Experiment Station, Forest Service
U.S. Department of Agriculture, Riverside,
California, U.S.A.

N.A. DEAN
Office of Agricultural and Fire Weather
National Weather Service, NOAA
University of California, Riverside,
California, U.S.A.

Abstract

Over the Labor Day period of August 30--September 2, 1987, dry lightning storms ignited fires in California that eventually burned nearly 320,000 hectares (800,000 acres), 1.9 billion board feet of timber, and led to 10 fatalities and an expenditure of $160,000,000 for fire suppression. Origins of the conflagration were studied by analyzing the 1000-hour timelag fuel moisture, which is used to track long-term fire potential, and by examining synoptic weather conditions during the Labor Day period. The results suggest that the fires of 1987 posed both long-term and short-term weather forecasting problems, which are identified in this paper.

Résumé

Au cours de la période de la fête du travail du 30 août--2 septembre 1987 des orages électriques sans précipitation ont enflammées des incendies en Californie, qui ont éventuellement détruit presalle 320,000 hectares (800,000 acres) 1,9 billion de pieds de planches de bois, et à provoqué 10 fatalités et une dépense de 160,000,000$ ufin de supprimer le feu. A étuide des origines de la conflagration s'est faite par l'analyse des teneurs en humidité des combustibles à variation sur 1000 heures observées, qui sert à dépister le potentiel à long terme du feu, et par l'examen des conditions météorologiques du cadre synoptique pendant la période de la fête du travail. Les résultats suggèrent que les incendies de 1987 ont démontrés des problèmes de prévision météorologique à long terme et à court terme, qui sont identifiés dans le présent article.

Introduction

California's climate of sunny days and mild winters is one of its enduring attractions. In certain cases, it is also a drawback, as it was in 1987, when the state suffered one of the most disastrous fire seasons in its history. The severity of the 1987 fire season was portended as early as April, when fuel moistures started dropping precipitously in California forests. The high fire threat became reality in late August, along the California-Oregon border, and the Sierra Nevada/Cascade Ranges. Dry lightning storms opened the fire season explosively, and within a week, more than 200,000 hectares (500,000 acres) of national forest lands within California---approximately five times the annual average---were devastated. Within 2 days, the Boise Interagency Fire Center committed all its resources to the fires raging in California and Oregon. A total force of 19,000 firefighters was mobilized, from 42 states. Fire threats forced the evacuation of the town of Seiad on the Klamath National Forest, the Pillsbury resort area on the Mendocino National Forest, and multiple evacuations of Milford, on the Plumas National Forest. Smoke from the fires was trapped under strong temperature inversions, creating respiratory problems and reduced visibilities. Temperatures dropped, apparently due to reduced insolation (Robock 1988). When the so-called Labor Day Fires were out, 10 firefighter fatalities were counted, nearly 320,000 hectares (800,000 acres) were burned, 1.9 billion board feet of timber were lost, and $160,000,000 was spent on suppression.

This paper describes the weather conditions, short-term and long-term, leading up to the Labor Day Fires of 1987 in California, the 1000-hr timelag fuel moisture equation currently used in the U.S. National Fire-Danger Rating System and an alternative formulation,

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

and the short-term weather phenomena that spawned widespread fires across the state. We argue that, for fire management purposes, knowledge of the state of the 1000-hr timelag fuel moisture was insufficient for predicting the magnitude of the California fires in 1987. Another forecasting challenge required knowledge of transient meteorological events, on a relatively small spatial scale. Short-term and long-term fire potential pose separate weather forecasting problems, which we attempt to describe.

Long-Term Development of Fire Potential

The 1987 California fires occurred in a relatively short time span, but the fire potential leading up to the actual event developed over a long period. A means by which fire potential is tracked is the so-called 1000-hr timelag fuel moisture (M), the mass ratio of water to fuel in dead roundwood fuels approximately 8 to 20 cm in diameter, or in the layer of dead material more than 10 cm below the surface of the forest floor (Deeming et al. 1977).

Let M_i represent the 1000-hr timelag fuel moisture on day i (Cohen and Deeming 1985):

$$M_i = M_{i-7} + (b_i - M_{i-7})[1 - 0.82/\exp(-0.168)] \qquad (1)$$

in which b_i is the running mean of daily equilibrium moisture contents, $\{f_j\}$, calculated for the 7 consecutive days ending on day i.

$$b_i = \sum_{j=i-6}^{i} f_j /7$$

Equation 1 can be simplified to

$$M_i = 0.693\ M_{i-7} + 0.307\ b_i \qquad (2)$$

The 1000-hr fuel moisture is dependent on temperature, relative humidity and precipitation through f. Equilibrium moisture content (EMC) is the moisture content that dead fuel attains at steady-state, when subjected to constant dry-bulb temperature and relative humidity. Although temperature and relative humidity can vary considerably from day to day (indeed, over the course of a day), marked daily changes are smoothed out in b_i. The constant coefficients in (2) are non-negative, and sum to 1. Therefore, the equation for M_i is effectively a weighted average of b_i and M_{i-7}. In fact, M_i can be expressed as a weighted average of the current and all past weekly EMC means, allowing the impact of past weather to be measured from a different perspective. Derivation of this alternative form is described below.

Equation 2 can be used recursively to solve M_i, M_{i-7}, etc., in terms of the weekly mean EMC ending on day i, i-7, etc., and the value of M that occurred 7 days earlier:

$$M_{i-7} = 0.693\ M_{i-14} + 0.307\ b_{i-7};$$

therefore,

$$M_i = 0.693^2\ M_{i-14} + 0.307\ [b_i + 0.693 b_{i-7}]$$

$$= 0.307 \sum_{j=0}^{\infty} 0.693^j b_{i-7j} \qquad (3)$$

Moreover, the sum of the infinite geometric series $\{0.693^j\}$ converges to 1/0.307; normalizing (dividing) each coefficient by 1/0.307 (bringing the constant 0.307 under the summation sign) gives the true weighting of the current and all past values of b to M:

$$M_i = \sum_{j=0}^{\infty} (0.307)0.693^j b_{i-7j} \qquad (4)$$

The coefficient of b decays exponentially, decreasing by the factor 0.693 for each preceding week. Equation 1 is from a parametric family that similarly describes dead fuel moisture variations in 1-, 10-, and 100-hr timelag fuel classes (Bradshaw et al. 1983); equivalent forms of (4), therefore, may be derived in each class. From (4), M_i clearly responds slowly to daily fluctuations in EMC, even if the daily changes are pronounced; M_i is instead driven by long-term weather conditions. Equation 4 also quantifies the relative importance of past weather. The cumulative sum of the coefficients shows, for example, that a weighted sum of the weekly mean EMCs truncated at lag 7--i.e., weather conditions of the past eight weeks--accounts for approximately 95% of the value of M_i. In the context of (4), weather conditions more than 2 months ago contribute little to the value of M_i.

With this perspective, we examined the 1000-hr timelag fuel moistures in California in 1987. Daily 1000-hr timelag fuel moistures were calculated for five stations, chosen according to their proximity to the fires, length of weather data record, and fire management recommendation. All stations represent interior California locations, at moderate to high elevations (Table 1).

Table 1.

Fire weather stations used to monitor 1000-hr timelag fuel moisture in California.

Station Name	Elevation (m)	National Forest
Oak Knoll	599	Klamath
Weaverville	624	Shasta-Trinity
Truckee	1830	Tahoe
Georgetown	915	El Dorado
Groveland	976	Stanislaus

The 1000-hr timelag fuel moisture series were calculated from the 1987 data obtained at the time this study commenced. Oak Knoll and Georgetown, the only stations with winter season data, recorded precipitous declines in 1000-hr fuel moisture beginning in April. Except for Georgetown, all five stations observed single-digit 1000-hr fuel moistures by May. Without exception, the traces were hovering at or below record minimum levels at the time the fires broke out at the end of August (fig. 1).

Climatic records show that California's monthly precipitation levels were sharply lower than normal in the 1986-87 winter. In the North Coast, Sacramento, and San Joaquin drainages, and in the Northeast Interior basins (fig. 2), April average precipitation was 43 mm (1.7 in) lower, and average temperature was approximately 3.2°C (5.8°F) higher (as computed from divisional averages). An upper-level ridge dominated the Pacific Southwest during most of the month, keeping the main part of low-pressure systems north of California. The steep decline in 1000-hr fuel moistures observed at Oak Knoll and Georgetown in April is consistent with this pattern. Higher-than-average temperatures and lower-than-average precipitation continued in the North Coast and Sacramento drainages through May. Warm and dry conditions usually prevail in July and August, but the large fuels probably were predisposed to fire even as summer began. But the occurrence of massive fires requires more than low fuel moistures. The Labor Day Fires were triggered by transient (short-term) weather conditions.

Synoptic Conditions During the "Lightning Bust"

In summer, the surface pressure pattern over California is usually defined by a thermal trough, extending from the southern deserts into the Central Valley. From 29 August through 2 September 1987, the thermal trough dominated most of California, and penetrated Oregon and Washington. Temperatures rose above the 100°F (37.8°C) mark in the interior valleys of California, and as far north as Portland, Oregon.

The 500 mb level was characterized by a long-wave trough over the United States, anchored by a low in the vicinity of the Hudson Bay. A major change in the 500 mb circulation over California occurred between 26-29 August, when a closed high developed over central Nevada, and a short-wave trough from the eastern Pacific moved through northern Washington, into southern Idaho. The trough deepened, forming a low over northeastern Colorado by 1200Z on 29 August. At that time, a low and associated vorticity maximum was positioned at 120°W, west-southwest of San Diego. The 500 mb analysis and a corresponding satellite image in the water vapor channel (fig.3) suggest that cold, moist air from the Colorado low was advected around the southern end of the Nevada high, into central California, toward the low off San Diego. Radiosonde data from Desert Rock, Nevada, (fig. 4) depicted a moist, unstable layer with easterly flow, roughly between 550-400 mb, at 1200Z 29 August. Thus were conditions set for the "lightning bust".

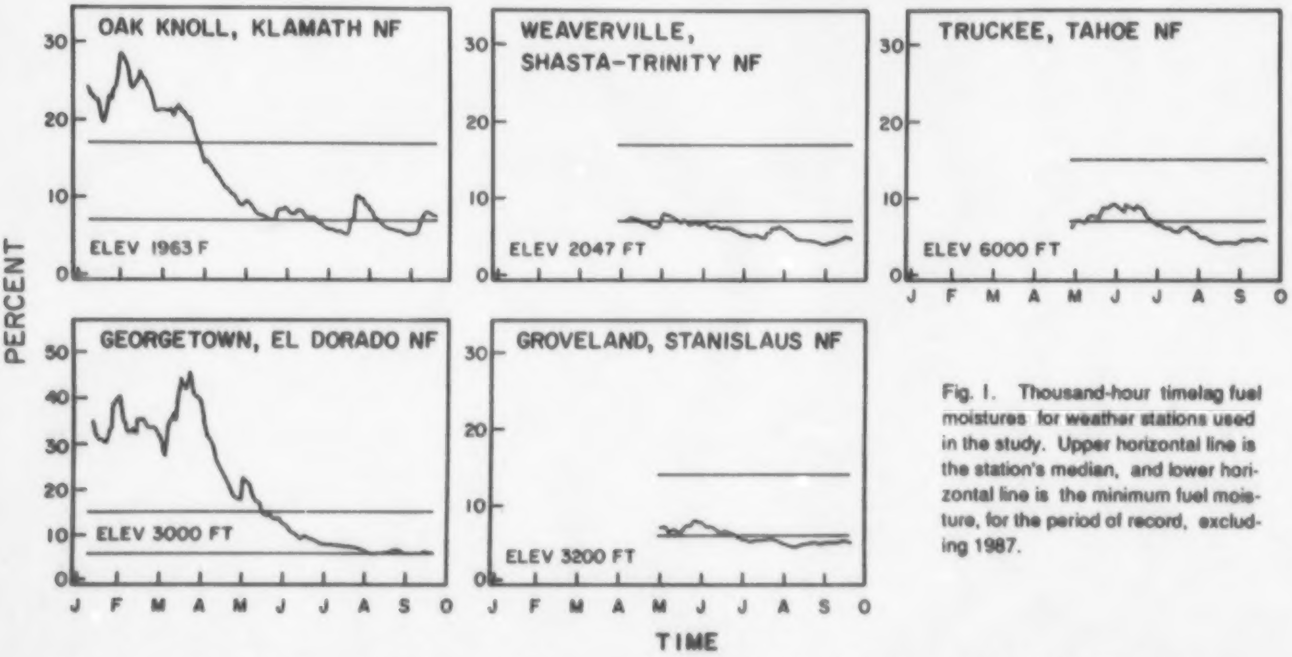


Fig. 1. Thousand-hour timelag fuel moistures for weather stations used in the study. Upper horizontal line is the station's median, and lower horizontal line is the minimum fuel moisture, for the period of record, excluding 1987.

FIG 1. Temperature and precipitation anomalies observed in California climatic divisions in April and May 1987.

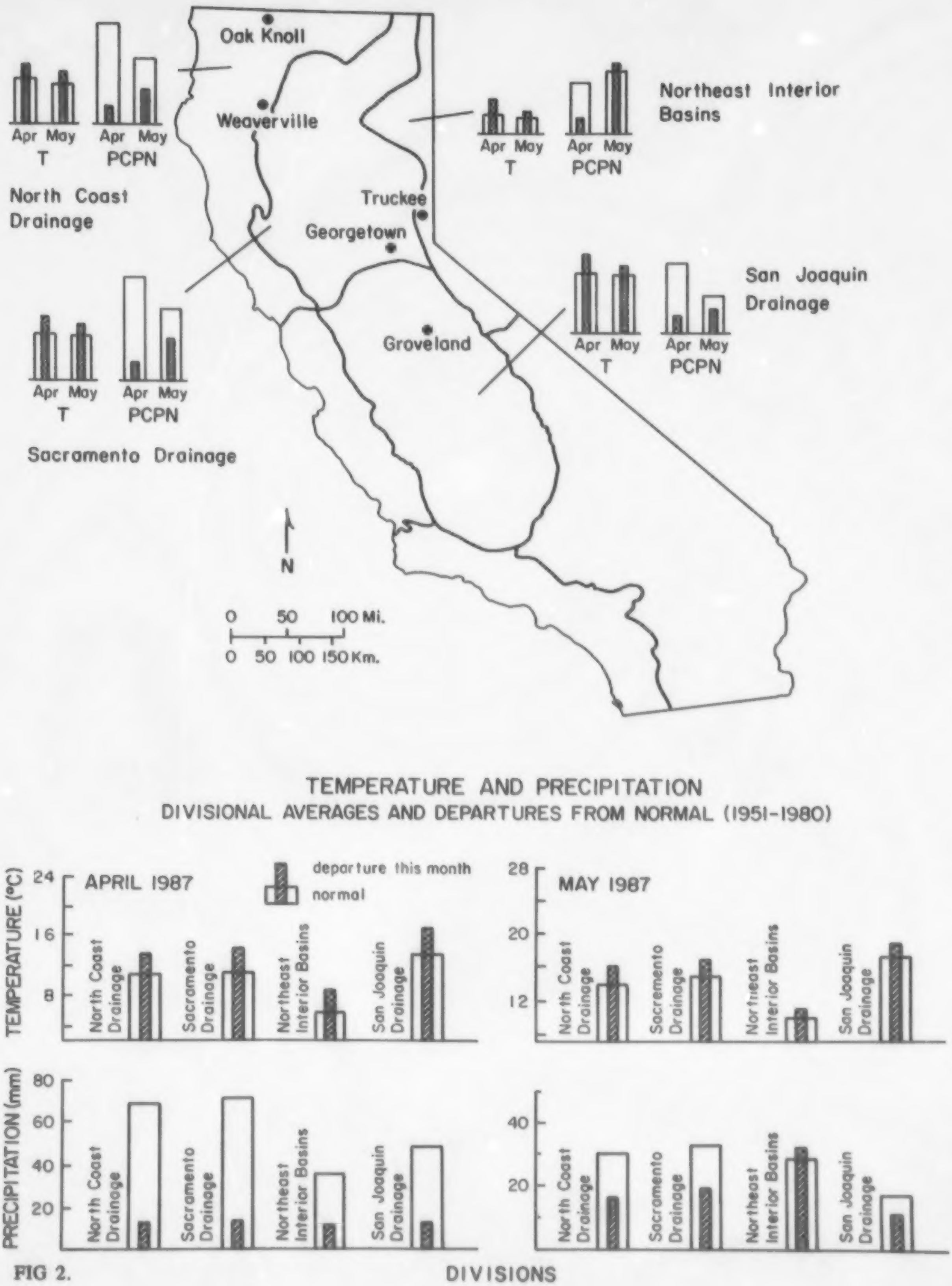
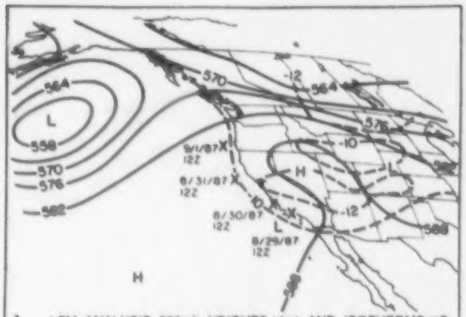
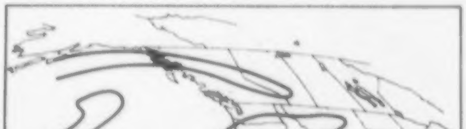

Oak Knoll
Weaverville
Truckee
Georgetown
Groveland
North Coast Drainage
Northeast Interior Basins
Sacramento Drainage
San Joaquin Drainage
Apr May
T
PCPN
N
0 50 100 Mi.
0 50 100 150 Km.
TEMPERATURE AND PRECIPITATION
DIVISIONAL AVERAGES AND DEPARTURES FROM NORMAL (1951-1980)
APRIL 1987
MAY 1987
departure this month
normal
TEMPERATURE (°C)
24
16
8
28
20
12
PRECIPITATION (mm)
80
60
40
20
North Coast Drainage
Sacramento Drainage
Northeast Interior Basins
San Joaquin Drainage
DIVISIONS

FIG 2.



A LFM ANALYSIS 500mb HEIGHTS (dm) AND ISOTHERMS (°C)
12Z SAT 29 AUG 1987



B SATELLITE WATER VAPOR IMAGE
12Z SAT 29 AUG 1987

Fig.3. Prevailing 500 mb conditions at the time of the "lightning bust" (A). Previous positions of the vorticity maximum associated with the California-Oregon thunderstorms are marked. Satellite image of water vapor data, corresponding to the 500 mb analysis, is shown in (B).

On 29 August 1987, the U.S. Bureau of Land Management's Automatic Lightning Detection System (Vance and Krider 1978) recorded 473 lightning strokes in the sector that circumscribes California---approximately 32°N 124°W to 32°N 114°W, to 42°N 114°W, to 42°N 124°W. On the previous day, only 10 strokes were recorded in this area. Lightning struck mostly along the Sierra Nevada and Cascade Ranges, after noon. Over the next 2 days, lightning would strike a broader area, with great intensity. From 29 August to 1 September, the 500 mb high moved slightly from central to northern Nevada. As it did, the vorticity maximum off southern California rotated around the high, introducing cold, moist upper-level air over the western part of the California-Oregon border. In combination with the hot daytime surface temperatures in the thermal trough, numerous thunderstorms developed in this area, causing 516 lightning strikes on 30 August. Lightning saturated the Sierra Nevada/Cascades---2,231 strokes were recorded from 30-31 August---as the high continued to feed moist, unstable air from the southeast. There was, however, no corresponding increase in precipitation.

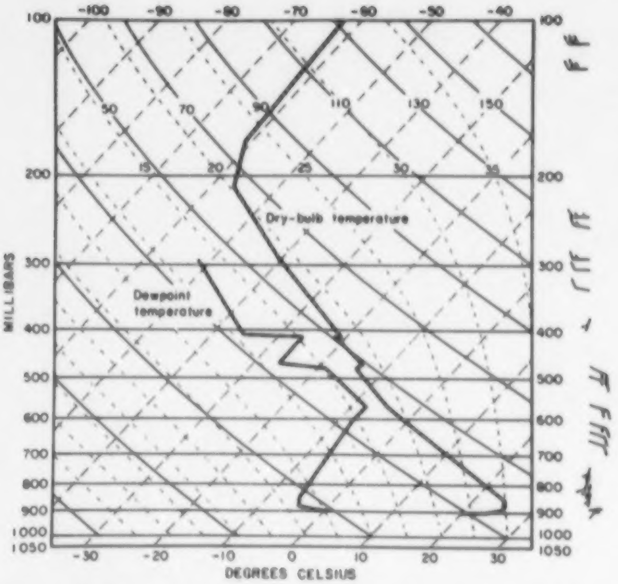


FIG 4. Radiosonde data from Desert Rock, Nevada, 1200 29 August 1987.

Radiosonde profiles favored formation of clouds at middle levels, and evaporation of precipitation in the dry subcloud layer---conditions typical of dry thunderstorms that are also apt to produce strong downdrafts (Schaefer 1986). Surface observations confirmed clouds based at 3650 m (12,000 ft) MSL, and isolated strong downdrafts. Lightning started numerous fires in the region, over the period 30 August - 2 September, and thus were the fires collectively called the Labor Day Fires. The Nevada high gradually dissipated and, by 3 September, was replaced by a trough which pushed into the Pacific Northwest, bringing a drier, more stable airmass over the area. Lightning activity diminished dramatically, except in the southern California deserts, but the fires raged on.

Discussion

Over the long-term, the lack of seasonal precipitation and the warmer than usual spring in California combined to drive fuel moistures down early. Equation 4 implies that a hot and dry April and May were sufficient to produce low 1000-hr fuel moistures by June. Summer weather further reduced 1000-hr fuel moistures to record low levels. In the short-term, a combination of factors---mid-level moisture and cold air advection, instability associated with a vorticity maximum, and orographic lifting induced by flow against the Sierra Nevada---triggered widespread thunderstorms of apparently unusual intensity. More lightning data and analysis are required before a clear lightning climatology emerges. The Automatic Lightning Detection System provides a promising tool to quantify lightning activity.

In retrospect, the California fires of 1987 posed both long- and short-range fire weather forecasting problems. The greater problem is the short-range, if only because we knew, in 1987, that the long-term conditions were severe, even before the Labor Day Fires occurred.

The challenge of predicting thunderstorm conditions accurately in space and time is great, even with complex mesoscale models. The relevant physical processes occur on a scale too small to be adequately observed, and modeled, except in subgrid parameterization schemes (Perkey 1986). In 1987, forecasters relied on considerable experience to predict dry thunderstorms.[1] For fire management, the challenge is to improve predictions of the intensity and location of lightning activity.

Assuming that 1000-hr fuel moistures adequately define a temporal scale for long-term fire potential, equation 4 provides a context for long-term fire weather forecasting. Great strides are being made in medium-range forecasts (Tribbia and Anthes 1987), which project daily weather conditions (nominally) 6-10 days ahead. These forecasts are driven by global scale models with grid resolutions typically on the order of 100 km. Too coarse to depict individual thunderstorms, the models may be used to predict 1000-hr fuel moistures. Medium-range forecasts provide temporal resolution to produce daily 1000-hr fuel moisture predictions over a 10-day period, but unless a daily forecast was necessary, a weekly 1000-hr fuel moisture prediction would be preferable, for two reasons. First, a forecast of a weekly mean is more accurate than a forecast of daily variations over a week. Second, the 1000-hr fuel moisture will not change drastically over a few days, as we have already argued.

Predictions of 1000-hr fuel moisture much beyond a week---and also beyond the range of medium-range forecast models---can be obtained from a sequence of weekly predictions of b. For example, to predict M four weeks hence (M_{i+28}), given the current value of M, use the equation:

$$\hat{M}_{i+28} = 0.693^4 M_i + 0.307 \sum_{j=1}^{4} 0.693^{4-j} \hat{b}_{i+7j}$$

The equation, derived in the same way as (3), places greater weight on more distant predictions of *b*. Unfortunately, the accuracy of predictions generally declines, as the forecast horizon is extended. Judicious use of weather forecasts requires the consideration of the uncertainties in the forecast, as well as the forecast itself.

Currently, no provisions exist to predict long-term weekly fire weather sequences. This is another challenge to fire weather forecasting.

Endnotes

[1] Personal communication, Ken Mielke, NWS Western Region, Salt Lake City, Utah, and John Snook, NWS Redding, California.

References

BRADSHAW, L.S., J.E. DEEMING, R.E. BURGAN, AND J.D. COHEN. 1983. The National Fire-Danger Rating System: Technical Documentation. USDA For. Serv. Gen. Tech. Rep. INT-169, Intermountain For. Rge. Exp. Sta., Ogden, UT. 44 p.

COHEN, J.D., AND J.E. DEEMING. 1985. The National Fire-Danger Rating System: basic equations. USDA For. Serv. Gen. Tech. Rep. PSW-82, Pacific Southwest For. Rge. Exp. Sta., Berkeley, CA. 16 p.

DEEMING, J.E., R.E. BURGAN, AND J.D. COHEN. 1977. The National Fire-Danger Rating System--1978. USDA For. Serv. Gen. Tech. Rep. INT-39, Intermountain For. Rge. Exp. Sta., Ogden, UT. 63 p.

PERKEY, D.J. 1986. Formulation of mesoscale numerical models. P. 573-596 In P.S. Ray, ed., Mesoscale Meteorology and Forecasting, Am. Meteor. Soc., Boston, MA.

ROBOCK, A. 1988. Enhancement of surface cooling due to forest fire smoke. Science. 242:911-913.

SCHAEFER, J.T. 1986. Severe thunderstorm forecasting: a historical perspective. Weather and Forecasting. 3&4:164-189.

TRIBBIA, J.J., and R.A. ANTHES. 1987. Scientific basis of modern weather prediction. Science. 237:493-499.

VANCE, D.L., AND E.P. KRIDER. 1978. Lightning detection systems for fire management. P.68-70. In Fifth Conf. Fire and For. Meteor., Atlantic City, NJ, Mar.14-16, 1978. Am. Meteor. Soc., Boston, MA.

Burning Out in Mountainous Terrain: Some Meteorological and Forest Fuel Considerations

R.A LANOVILLE AND W.M. MAWDSLEY
NWT Department of Renewable Resources
Fort Smith, Northwest Territories

Abstract

A combination of valley winds, instability in the lower atmosphere, and dryness of the fine forest fuels were used as criteria to decide whether or not to ignite a burnout along a V-shaped valley, using a helitorch, to control the spread of a wildfire. The fire was located in mountainous terrain 60 kilometers northwest of Fort Liard, N.W.T. Atmospheric instability was needed to lift the smoke from the burnout clear of the narrow valley to allow access by helitankers and follow-up ground operations. The valley winds had to be favorable; the fine fuels sufficiently dry to allow full tree crown combustion without excessive spotting. This paper describes how the meteorological and forest fuel measurements were made and how the combination of these inputs determined the decision to conduct the burnout operation of August 4, 1984.

Résumé

Nous avons utilisé une combinaison de brises de vallée, d'instabilité dans la partie inférieure de l'atmosphère et de sécheresse des combustibles légers de forêt comme critères pour décider s'il fallait ou non allumer un contre-feu le long d'une vallée en V à l'aide d'une hélitorche pour contrôler la propagation d'un incendie forestier. L'incendie faisait rage à 60 km au nord-ouest de Fort Liard dans les T.N.-O., en terrain montagneux. Il fallait que l'atmosphère soit instable pour que la fumée du contre-feu libère l'étroite vallée afin de donner accès au secteur aux hélicoptères-citernes et de poursuivre les opérations au sol. Les brises de vallée devaient être favorables et les combustibles légers devaient être suffisamment secs pour que l'ensemble de la cime des arbres brûle sans que le feu ne se dissémine à l'excès. Le présent article décrit comment les conditions météorologiques et les paramètres des combustibles de forêt ont été mesurés et comment ces données combinées ont permis de décider d'allumer un contre-feu le 4 août 1984.

Introduction

BN-16, the fire's designation, was discovered by Nahanni Butte Tower at 2200 MDT, July 29, 1984. The fire was located in mountainous terrain 60 kilometers northwest of Fort Liard, N.W.T. The fire was directly attacked and held to 70.0 hectares until August 3, when it spotted over its western fireguard and doubled in size. In the opinion of the Fire Boss, continuing the direct attack strategy would have been a venturous enterprise, especially along the fire's southern flank, where it paralleled a steeply-sloped side valley. Consequently, a burnout plan was developed.

Burning out is a fire suppression operation where fire is set along the inside edge of a control line or natural barrier to consume unburned fuel between the line and the fire perimeter, thereby reinforcing the existing line and speeding up the control effort (Merrill and Alexander 1987). This strategy, when conducted through careful planning, is not a sensational, last-ditch effort to control the spread of a fire but rather a safe, viable alternative to direct attack methods. Careful attention must be paid, however, to the fire environment before burning out is attempted. The purpose of this paper is to document the fire environment on BN-16 leading up to and during the burnout operation with particular emphasis on monitoring winds in mountainous terrain, determining lower atmospheric stability, and assessing the dryness of the forest fuels.

Topography

The fire was located in the rugged Liard Range of the Franklin Mountains. The Liard Range is oriented NNW-SSE; its western slopes face the Kotaneelee River whose broad valley is oriented in the same direction (Figure 1). The fire was situated on a southerly aspect overlooking Burnt Creek, a steeply-sloped (50-60 degrees), V-shaped, side valley oriented NE-SW. Upon leaving the Liard Range, Burnt Creek and Sully Creek, the next drainage north, cut sinuous paths about 50 meters in depth across the gently undulating terrain of the Kotaneelee River Valley and empty into the Kotaneelee River located about 8 kilometers to the west.

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

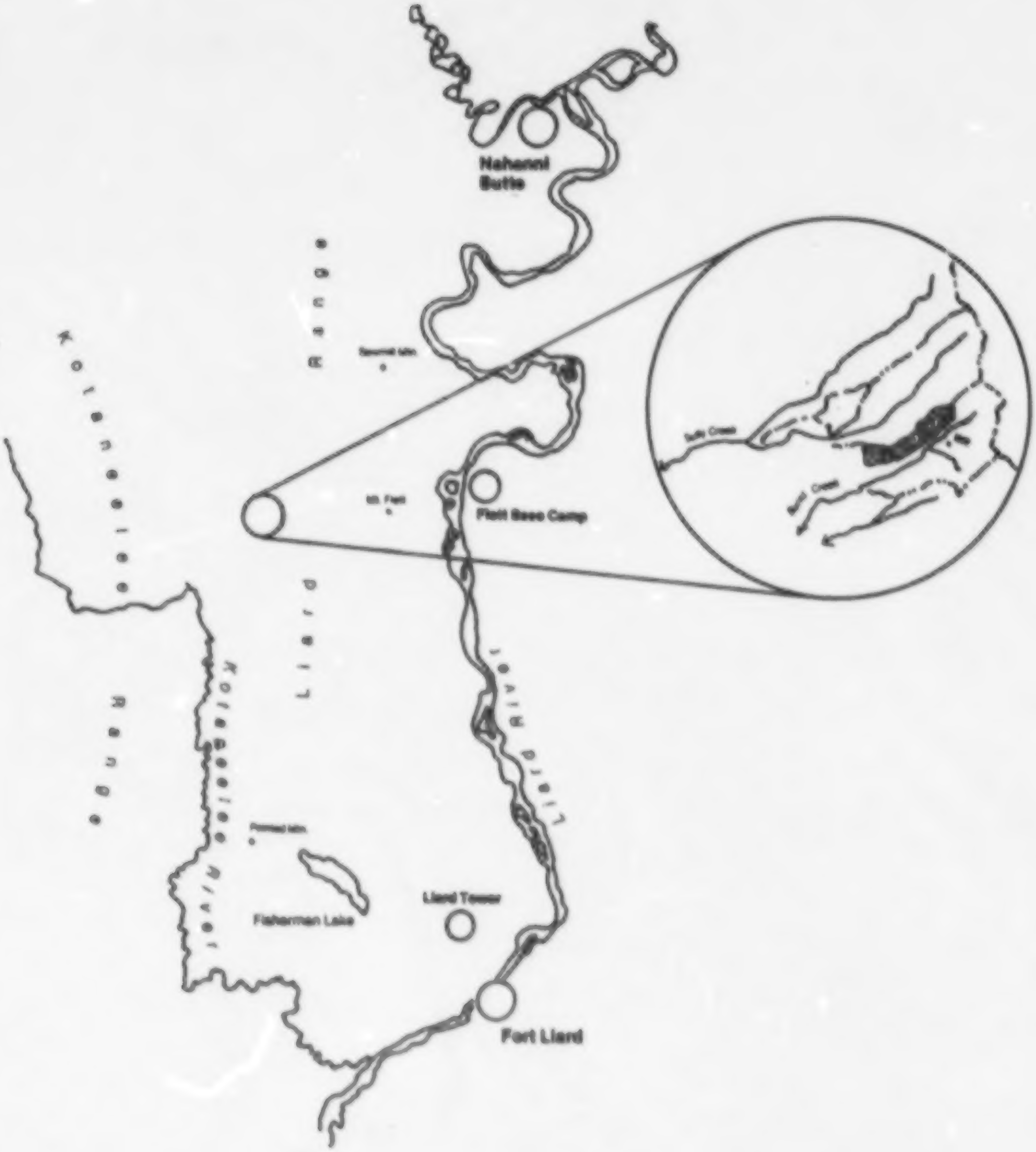

Nahanni Butte
Liard Range
Sentinel Mtn.
Kotaneelee Range
Mt. Flett
Flett Base Camp
Sully Creek
Burnt Creek
Liard River
Kotaneelee River
Pointed Mtn.
Fisherman Lake
Liard Tower
Fort Liard

FIG. 1. The location of BN-16, in the Liard Mountain Range, 60 kilometers NW of Fort Liard, N.W.T. The inset shows the location and orientation of Burnt and Sully Creeks and the shape and orientation of the fire on August 4, 1984.

Forest Fuels

The forest fuel complex in the fire area was made up mainly of mature stands of black and white spruce. Along the valley bottoms, small clumps of jack pine and balsam fir were intermingled with the spruce. In the upper reaches of Burnt and Sully Creeks and part way along the ridge which separated them, the spruce was open-grown with tree crowns extending to the forest floor. Tree heights varied between 3 and 10 meters. The forest floor consisted mainly of lichens and mats of low, prostrate shrubs. Elsewhere, the spruce was moderately well-stocked with tree heights varying between 10 and 20 meters and tree crowns extending to within 1 meter of the forest floor. In these areas, the forest floor consisted mainly of feather mosses. In all areas, dead, down woody material was scarce or absent.

Weather Observations

A local fire weather network was set up on July 31. Hourly observations, during daylight hours, were received from Liard Tower, located 55 kilometers to the SSE. The tower was about the same elevation and exposure as the fire site. An automatic weather station was established at the fire site where hourly temperature, relative humidity, wind speed, wind direction, and rainfall were recorded. A field portable manual station was installed at the Flett Base Camp (fire camp). The weather stations were established according to Turner and Lawson (1978). In addition to taking weather readings, the wind directions in the fire area, as reflected by the ascent of the smoke, were observed and recorded several times a day.

Antecedent Weather

During the period July 31 to August 3, the fire area was under the influence of an upper high pressure ridge. The air mass was warm, dry, and convectively unstable. At the surface, the daytime maximum temperatures varied between 25°C and 30° C; the relative humidity varied between 30 and 40 percent. The gradient wind was slack and generally insignificant in the main valleys like the Liard and Kotaneelee. In the mountainous areas, the winds were local, directed by the terrain and the effects of daytime heating and nighttime cooling. In general, the afternoon winds at the fire site were upvalley and upslope. In the late evening, this pattern was reversed. On August 3, a moderate northerly flow established itself over the fire and persisted throughout the day causing the wind to channel downvalley along the ridge top between Burnt and Sully Creeks.

The 1300 MDT weather data gathered from the fire site was entered into the Canadian Forest Fire Weather (CFFWI) System (Van Wagner 1974, Van Wagner 1987, Turner and Lawson 1978, Canadian Forestry Service 1984, Van Wagner and Pickett 1985) to determine the general burning conditions during the peak burning periods. The August 1 start-up values for the Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC) and Drought Code (DC) components of the CFFWI System were determined from values calculated at Liard Tower.

Fire Chronology

At 0930 MDT on July 30, (no suppression action was taken on July 29), an initial attack crew from Flett Base Camp arrived at the fire. They found a 20 hectare fire located on the south facing slope of Burnt Creek. From its mid-slope location, the fire was candling and torching and spreading with a light SW wind upvalley and upslope. At 1120 MDT, the DC6 tanker from Hay River arrived and put down a retardant line along the western flank of the fire. Working with a 206L helicopter, the 10 man suppression crew secured the retardant line along the western flank and established a fire control line along the ridge which separated Burnt Creek from Sully Creek. During the day, the fire burned unchecked along its eastern flank. The eastward spread was accelerated by the combined effect of valley winds (SW) and slope. The fire burned intensely removing all the tree crowns and continued spreading until it ran into sparce fuels, and open, rocky areas at the head of Burnt Creek. By evening, the fire size was estimated to be 70.0 hectares.

For the next three days, July 31 to August 2, the fire made no appreciable spread. It was blocked off by the retardant and hand-tool line on the western flank; it had burned upslope to the ridge, between the creeks, where it was stopped by suppression action; and it had burned into sparce fuels intermingled with open, rocky areas on the eastern flank. The only direction of fire spread was along its southern flank, against the slope and the wind. Progress was made by creeping downslope and gaining access to the downhill side of the spruce trees, followed by intermittent torching of the trees. The resultant burn was a near total removal of both the surface and aerial fuels. This downhill creeping and intermittent torching began about 1400 MDT each day and continued until about 2100 MDT, which was about one hour past sunset on the slope.

On August 3, beginning at 0500 MDT and lasting until 2200 MDT, the wind at the fire site switched from southerly (prevailing direction over the past three days) to northerly. During the morning, the wind turned downvalley, or northeasterly, along the ridge between the creeks. With the daytime heating, the wind direction was influenced by an upslope component so that the resultant wind above Burnt Creek was cross-slope (the same as a SE wind). These wind directions were easily observed from the movement of the smoke. As the smoke ascended, the wind direction switched from SE above Burnt Creek to NE along the ridge to NW above the valleys, curling the smoke plume up, over, and then away from the fire.

On the western flank, between 1500 MDT and 1800 MDT, the fire spread downslope, from the top of the ridge between the two creeks, into the Kotaneelee River Valley. The surface winds were SE and the winds aloft were NW. The smoke plume ascended with the SE surface wind then spiralled counterclockwise into the NW flow. At the ridge top, the wind was from the NE and was so strong and gusty that helicopters could not land on the ridge. The presence of this strong wind had the effect of pushing the spiralling smoke plume over unburned fuel on the downslope side of the fire front, and showering it with fire brands. The spot fires rapidly crowned and spread upslope to join the main fire. With the increase in heat output, the smoke plume straightened up, temporarily removing the source of more spot fires. When the surge of heat dissipated, the smoke plume curled back over the unburned fuel. More spot fires would then develop repeating the process. From 1800 MDT to 2130 MDT, the downslope propagation returned to the more familiar downslope creeping and torching. This fire behavior coincided with reduced windspeed along the ridge.

On the southern flank, the fire spread from 1500 MDT to 2130 MDT was downvalley and cross-slope. The fire behavior was characterized by frequent episodes of candling and short distance runs of crowning fire, which transformed the once serrated edge into an undulating one. In several places, the southerly flank was between 25 and 100 meters above Burnt Creek.

Burnout Operation

At the end of the burning period on August 3, the fire situation was as follows:

1. The fire size was about 150 hectares. The fire was controlled along the ridge between the creeks and along the eastern flank where it had spread into open rock.
2. The fire was burning out of control along the southern flank above Burnt Creek and along the western flank facing the Kotaneelee River Valley.
3. There was no water in Burnt Creek. The nearest reliable water supply was the Kotaneelee River located 8 kilometers to the west.
4. Access to the fire was limited. The main helipads were located on the ridge between the creeks. Access to the southern flank, by air, was impossible because of the narrowness of the valley.

Fire control along the southern flank was most problematic because of the steep rocky slopes, the lack of water, and the inaccessibility by air. A direct attack strategy along this flank would be slow, costly, and dangerous. Given the right conditions, burning out was a viable alternative control strategy.

A burnout plan was developed with the following criteria established for its implementation:

1. In the interest of safety, the burnout would be done using a helitorch against natural and man-made fuelbreaks, with helitanker support (Figure 2). Ground crews would follow up as required for mop-up.
2. The burning out would be done with wind speeds less than 15 km/h and wind directions from the south or southwest.
3. The lower atmosphere had to be sufficiently unstable to allow a strong, free-rising smoke column to form.
4. The FFMC value had to be in the range 85 to 91.

The established criteria were met on August 4. The spot forecast for the afternoon of August 4 called for light southerly or southwesterly winds. The 1800 MDT surface analysis, given in Figure 3, validates the forecast winds for the fire area. Beginning at 0845 MDT, a temperature profile of the lower atmosphere was done by recording air temperature readings at 170 meter intervals in a helicopter. As can be seen from Figure 4, there was an inversion below the elevation of the fire and unstable air above it. The sounding from the Fort Nelson B.C. Upper Air Station at 0600 MDT indicated a generally unstable, dry, air mass over the entire region. The FFMC, calculated first from forecast weather data and confirmed by the 1300 MDT observations at the fire site was 91 (Table 1).

Table 1. The 1300 MDT fire weather observations and FWI System components for the fire site, August 1 to August 4, 1984.

	Temp (° C)	RH (%)	10-m Wind (km/h)	Rain (mm)	FWI System Components					
					FFMC	DMC	DC	ISI	BUI	FWI
August 1	24.0	40	10	0.0	89	43	222	7	58	18
August 2	22.3	32	20	0.0	91	46	229	13	62	30
August 3	22.5	33	12	0.0	91	50	236	9	65	23
August 4	24.7	35	7	0.0	91	53	244	7	69	20

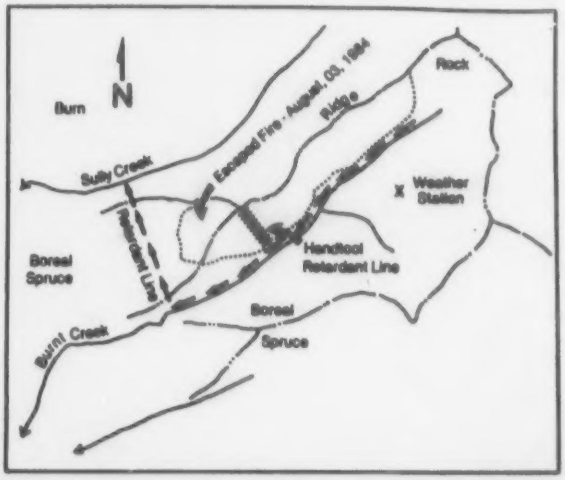


FIG. 2. The arrows show the progression of the burnout operation at BN-16 on August 4, 1984.

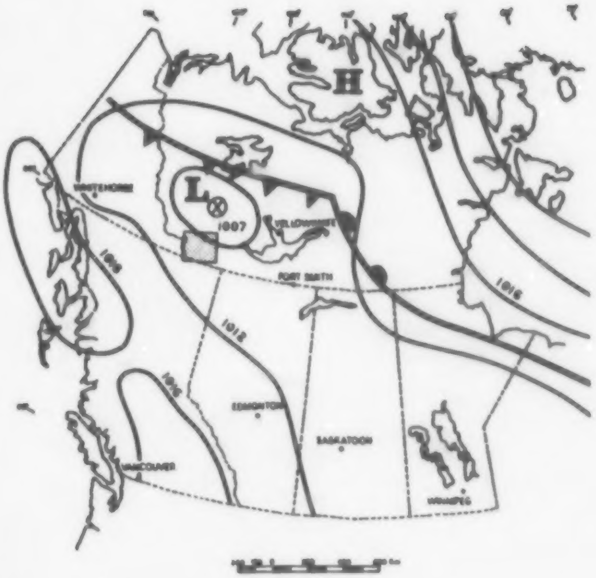


FIG. 3. Surface analysis 1800 MDT, August 4, 1984.

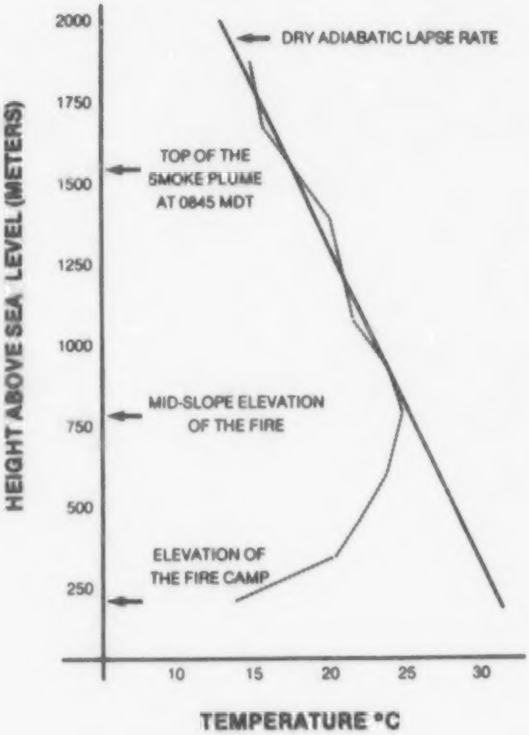


FIG. 4. Temperature sounding of the lower atmoshpere above BN-16, 0845 MDT, August 4, 1984.

No preparation for the burnout operation was required along Burnt Creek. The creekbed was dry and consisted on cobble-sized rock free of vegetation. The vegetation at the head of the creek would not carry a fire. With the prescribed upslope winds, the helitorch could start at the head of Burnt Creek, which was desired, and follow with ease, along the edge of the creek.

The western flank, on the other hand, required a control line of long term retardant. The control line was located at the base of the mountain and ran in an straight line between Burnt Creek and Sully Creeks, a distance of about 1250 m. The line of retardant was established using a DC-6 air tanker and was in place at 1400 MDT.

At 1400 MDT, the fire was becoming active. Creeping surface fires backing against the slope and wind were evident along the southern and western flanks. Episodes of torching were common place. The smoke was rising freely on all active sections of the fire forming loose ascending plumes. All the smoke in Burnt Creek was lifting clear of the narrow valley. The weather readings at the fire were as follows: temperature (26.4° C), relative humidity (33%), wind direction (S), and wind speed (5.5 km/h).

The burnout commenced at 1430 MDT at the head of Burnt Creek and proceeded downvalley toward the freshly established retardant line. Behind the helitorch, an intense line-fire developed within 1 to 2 minutes removing nearly all the surface and crown fuels from the creek bank to the main fire edge. The flaming zone dissipated about 15 minutes after ignition. By 1630 MDT, the entire length of Burnt Creek, from its head to the retardant line, was cleanly burned. The burnout operation was followed by helitanking using 3 medium lift helicopters. Except for one spot fire, which started in a log jam on Burnt Creek, the operation was a total success.

Having secured the fireline along Burnt Creek, the western flank was burned out against the retardant line. Again, a crowning, line-fire developed within minutes behind the helitorch and spread rapidly upslope to meet the main fire. The helitanking operation continued behind the helitorch, as was the procedure in Burnt Creek.

Discussion

Setting up a local fire weather network, which is the responsibility of the fire management team, is highly recommended. In mountainous terrain, a weather station should be set up near the fire as the conditions at the fire may be different than those elsewhere. For example, the diurnal cycle of relative humidity in the Kotaneelee River Valley was different than that at BN-16. In the river valley, the maximum overnight relative humidity values varied between 90 and 95 percent; at the fire, the values varied between 35 and 40 percent. An inversion capped the valley each morning, while at the same time, the fire was above it.

In calculating the components of the CFFWI System, it is advisable to set the start-up values of the FFMC, DMC, and DC from values calculated for nearby weather stations (Lanoville and Schmidt 1984, DeGroot and Alexander 1986, Alexander et al. 1989). In this case, the DMC and DC values from Liard Tower were used without adjustment; the FFMC was set at a value of 85. This value could have been fine-tuned by using observed fire behavior, however, this was not judged to be necessary.

Daily fire behavior forecasts were prepared from the fire weather spot-forecasts, the CFFWI System components, and the Canadian Forest Fire Behavior Prediction (FBP) System (Alexander et al., 1984). Making regular fire behavior observations proved to enhance the quality of the forecasts. As much as anything else, it was this first-hand experience which determined the criteria for the burnout operation.

A crown fire, developing immediately after ignition, was required to remove all the forest fuels from the creek edge and along the retardant control line. With most of the fuels gone, there would be little resistance to mopping-up using helitankers immediately behind the torch. A FFMC value of 91 (maximum value allowed) with no wind (minimum speed) translates to a rate of spread of 15 meters per minute on a 50 percent slope. A FFMC value of 85 (minimum allowed) and a windspeed of 15 km/h (maximum allowed) translates to a rate of spread of 15 meters per minute on a 50 percent slope. For fires burning upslope (50 percent slope) in the boreal spruce fuel type, the crown fire threshold rate of spread is 14 meters per minute (Alexander et al. 1984). The slopes above Burnt Creek greatly exceeded 50 percent whereas the slopes above the retardant control line were about 50 percent. It was for these latter slopes that the range of FFMC values were set.

One of the worse things to happen during a burnout operation is to be smoked in. This would obviously compromise the whole operation and even place those conducting it in jeopardy. The on-site temperature sounding was done to obtain specific information about atmospheric stability in the lowest layers. This information coupled with the upper air analysis confirmed that smoke would not be a problem on August 4, 1984. The favorable winds and slope further ensured that all the smoke would entrain into the main column.

After two days of patrol, Burnt Creek and the western flank had no hotspots left to extinguish. The burnout followed immediately by helitanking proved to be an effective strategy. The appropriateness of its implementation was dependent, however, upon certain established criteria being met. Had the criteria not been met, the Fire Boss would have had to abandon Burnt Creek for safety reasons.

Endnotes

[1] All times in this report are Mountain Daylight Time (MDT).

References

ALEXANDER, M.E., B.D. LAWSON, B.J. STOCKS, AND C.E. VAN WAGNER (listed in alphabetical order). 1984. User guide to the Canadian Forest Fire Behavior Prediction System: rate of spread relationships. Interim edition. Environment Canada, Canadian Forestry Service, Fire Danger Group. 73 p. + Supplements. (1st Printing - July 1984; Revision & 2nd Printing - Sept. 1984)

ALEXANDER, M.E., B.J. STOCKS, AND B.D. LAWSON. 1989. Fire behavior in black spruce-lichen woodland: the Porter Lake Project. Canadian Forestry Service, Northern Forest Centre, Edmonton, Alta. Inf. Rep. NOR-X-000. [in press].

CANADIAN FORESTRY SERVICE. 1984. Tables for the Canadian Forest Fire Weather Index System. Fourth edition. Environment Canada, Canadian Forestry Service, Ottawa, Ont. Forestry Technical Report 25. 48 p.

DE GROOT, W.J., AND M.E. ALEXANDER. 1986. Wildfire behavior on the Canadian Shield: a case study of the 1980 Chackukew Fire, east-central Saskatchewan. Proc. Third Central Region Fire Weather Committee Sci. and Tech. Seminar (April. 3, Winnipeg, Man.). Can. For. Serv., West. & North. Reg., North. For. Cent., Edmonton, Alta., Study NOR-5-05 (NOR-5-191) File Rep. No. 16, p. 23-45.

LANOVILLE, R.A., AND R.E. SCHMIDT. 1985. Wildfire documentation in the Northwest Territories: a case study of Fort Simpson-40-1983. Proc. Second Western Region Fire Weather Committee Sci. and Tech. Seminar (Mar. 6, 1984, Edmonton, Alta.). Can. For. Serv., North. For. Res. Cent., Edmonton, Alta., Study NOR-5-191 File Rep. No. 9, p. 17-22.

MERRILL, D.F., AND M.E. ALEXANDER (editors). 1987. Glossary of forest fire management terms. Fourth edition. Natl. Res. Counc. Can., Can. Comm. For. Fire Manage., Ottawa, Ont. Publ. NRCC No. 26516. 91 p.

TURNER, J.A., AND B.D. LAWSON. 1978. Weather in the Canadian Forest Fire Danger Rating System: a user guide to national standards and practices. Environment Canada, Canadian Forestry Service, Pacific Forest Research Centre, Victoria, B.C. Information Report BC-X-177. 40 p.

VAN WAGNER, C.E. 1974. Structure of the Canadian Forest Fire Weather Index System. Environment Canada, Canadian Forestry Service, Ottawa, Ont. Publication No. 1333. 44 p.

VAN WAGNER, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Government of Canada, Canadian Forestry Service, Ottawa, Ont. Forestry Technical Report 35. 37 p.

VAN WAGNER, C.E., AND T.L. PICKETT. 1985. Equations and FORTRAN program for the Canadian Forest Fire Weather Index System. Government of Canada, Canadian Forestry Service, Ottawa, Ont. Forestry Technical Report 33. 18 p.

New Technologies: A Total System Perspective

S.E. GORDON
University of Idaho
Moscow, Idaho

Abstract

New technologies are changing the face of the workplace. In fire and forest meteorology, such technologies can greatly enhance the capabilities of man to deal with complex and rapidly changing information. However, with such advances come questions and issues about how the technologies will ultimately affect people and the way they perform their jobs. This presentation addresses some of the issues and concerns that have been identified within the field of human factors. It is suggested that a total system perspective be adopted, a perspective that treats both human and machine as symbiotic components within one complex system. This total complex system must be adequately considered and modeled for optimal end performance.

Résumé

Les nouvelles technologies sont entrain de changer le milieu de travail. Dans le domaine de la météorologie forestière et d'incendies, de telles technologies peuvent améliorer de beaucoup les capacités de l'homme à transiger avec l'information complexe qui change rapidement. Cependant de telles avances amènent des questions et des issues à savoir la façon ultime dont les gens et la manière qu'elles accomplissent leurs tâches seront affectées. Cette présentation adresse quelques unes des issues et préocupations qui ont été identifiées dans le domaine des facteurs humains. On suggèrre qu'une perspective totale du système soit adoptée, une qui traite l'humain et la machine comme composante symbolique à l'intérieur d'un système complexe. Ce système complexe doit être considéré de façon adéquate et modelé pour assurer une performance optinale à la fin.

While many of you may be familiar with the field of human factors, I would like to begin by briefly describing what we do, and what are the important parts of my field. Then I will review some of the key issues that we have seen emerging as a result of the introduction of computer technology.

In human factors, our goal is to work with designers to make a product or environment that is optimal for the person who uses it. An example comes from the automotive industry; automotive manufacturers invariably have one or more human factors engineers to help the design team determine the controls and displays placement on the car dashboard. Actually, human factors can be applied to almost anything that people do, make, or use; from something as simple as the reach toothbrush to something as complicated as an orbiting spacestation, or an expert system to help doctors make medical diagnoses.

When I say that we try to optimize these systems, I mean several things. We try to make systems that are safe for people (such as in forestry operations), things that are efficient, and things that are easy to use (as in computer software). We try to make systems that enhance performance, and perhaps are even fun to use.

People who are familiar with human factors tend to think only of the "knobs and dials" aspects of mechanical systems - again, the automobile dashboard idea. Or people often think of the phrase "making it user friendly." But these things are only a part of the whole picture. The whole picture is what I refer to as designing for the Total System. The Total System is that symbiotic relationship between a product and the person who uses it. Whenever a product or environment is designed, it must be done by evaluating how the Total System will operate. For example, in the automotive industry, the Total System is the combination of the car and the driver. The car may work fine, but if the driver drives off the road, the total system itself is a failure.

The first important consideration in designing for the total system is knowledge of the user, both cognitive and physiological aspects, so the (designed) system characteristics map onto human characteristics. This is not always just a matter of applying intuition and common sense. Perhaps the easiest way to demonstrate this is to give an example.

In the early 1970's the Navy decided they needed a simulator to train pilots to land their jets on an aircraft carrier. The obvious motivation was that they did not want novice pilots up training in a real plane. If the pilot didn't do it right, there would be some pretty serious consequences (like going off the end of the runway). So they built the simulator. They built it on a motion platform so the pilot felt the rolling and pitching, the changing altitudes, and so on. The simulator had a large wrap-around display depicting the view one would see out of the aircraft. All the

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

controls and displays were hooked up to a computer system so that pilot actions were fed into the computer and it displayed the appropriate computer-generated pictures on the screen. After spending millions on this project, the designers decided to try it on experience trained pilots. They brought in seasoned pilots who proceeded to crash the simulator, repeatedly. In addition, the pilots told them that "there's a problem somewhere because it doesn't act like my jet at all". So the engineers tried to diagnose the problem, going back and redoing all the calculations, making sure the display projected exactly the correct retinal image, and so forth. Unable to find anything wrong, they called in a human factors specialist. The specialist looked at the simulator and said "Ah yes, it's a problem of visual accomodation".

The easiest way to explain the phenomenon of visual accomodation is to let you experience it directly. One easy way to accomplish this is to hold your left hand all the way out in front of you with your thumb up. Focus on that thumb for a few seconds. Now bring you right thumb across in front of you closer than your left hand. Put it where you can still see your left thumb. Change your focus from your left thumb to your right thumb. You should notice that your left thumb now looks smaller and further away, even 'though it hasn't actually moved at all. That is visual accomodation: where you focus your eyes directly determines the size that objects will appear to you.

Visual accomodation caused the problem in the simulator. When a fighter pilot is up in his jet, coming in to land on the aircraft carrier, he looks down and out of his window to the aircraft carrier, essentially focusing at infinity. He uses that image as a visual cue to decide how high his altitude should be as he comes in to land. It's a visual cue that the pilots have learned and practiced over and over again.

However, when they are put in a simulator, they are focusing on a screen that is three feet in front of them, not out at infinity. They have brought their focus in closer, with the result that the ship, which should look the same size as in real life, actually looks smaller. They decide that the ship is still far away, meaning they should be up high. As they get close to the ship, they suddenly realize they are too high, but it is too late.

In this particular example, the missing piece was relatively simple, knowledge of the human visual system. The navy was fortunate in that everything was run by computer modeling. All they had to do was go back and increase the size of the ship display on the screen by approximately 20%. Unfortunately, other projects have had to be scrapped and entirely rebuilt from scratch because of human problems factors such as the one I have described.

The point behind this story is that sometimes it's not just a matter of applying common sense, or things that we think we know about. And much of the mechanical engineering industry (and almost all of U.S. Department of Defense groups) have learned that it is almost always easier and more economical to apply human factors from the very beginning.

What does this have to do with this conference and new technology? Computer-based technology provides systems that are built to be used by people, just as much as a jet airplane or a car. As such, we need to submit it to the same types of human factors analysis. When we design it, we need to think about what's going to happen with the user? What's going to happen to the "Total System"?

Computer technology is making rapid headway into all facets of life. Much of the work done in human factors deals with interfacing computers with people. I can't review all of this work, however, I will give you two more examples of the kind of problems that can arise from a failure to adequately evaluate product design from a total system perspective.

The first example involves current trends in the nuclear industry. In Europe and the United States, for the last ten years or so, people have been busy trying to design computers to help the nuclear power plant operators deal with a very complex system. It is generally agreed that the operators are not capable of optimally understanding, thinking about, and making decisions about all of the complex information with which they are typically faced. As an answer, computerized technology has been implemented as much as possible.

The end result is that they now have computer systems to monitor the state of the plant, control various functions in the plant, and there are even expert systems that perform malfunction diagnosis. If there is a a malfunction or accident, the sensory information goes into the expert system and the expert system provides the most likely cause of the malfunction and suggests a course of action.

In theory, this seems like a good idea. However, I have seen indications that there may be problems looming on the horizon. For example, I recently read a newspaper article that indicated they were having problems with the operators falling asleep on the job. That was hardly surprising because the computers are now doing everything that the operators used to do, and this means that the operators have nothing to do. Well, I was glad to see in the paper that someone had come up with a solution; they would just give the operators less comfortable chairs.

While this is amusing, it points to a serious problem. When designers don't look ahead and adequately foresee the effects of automation on the user, some undesirable effects can result. A second example of failure to model the total system comes from the airline industry. The problem concerns the introduction of autopilots. As most of you are probably aware, an autopilot is a flight aid that basically flies the airplane for the pilot. By turning on the autopilot, the captain is free to get up, move around, or attend to other matters.

At first everyone, including the pilots, thought this was a very valuable tool with relatively few disadvantages. Unfortunately, there have been some problems with the use of autopilots that have only recently come to light. The first problem is that pilots sometimes place too much trust in an automated system. One such instance occurred in 1972. The Eastern L-1011 flight-deck personnel, while in a holding pattern, were attempting to diagnose the cause of a malfunctioning landing-gear indicator. They had faith that the autopilot would hold them at altitude while their full attention was diverted to diagnosis. The autopilot did not hold, and the plane gradually descended into the Everglades with 99 fatalities. It's difficult to know what an autopilot can do, what it can't do, when it should be left in charge and when it shouldn't.

Another problem that has occurred as a result of autopilots is called the man-out-of-the-loop problem. Stated briefly, when the operator is replaced by an automatic controller, he/she reduces the level of interaction of familiarity with the state of the system. When a malfunction does occur, the operator is slower to detect it and will require longer to "jump back into the loop" and exert appropriate control actions.

As an example, there was a trans-Pacific B-747 flying at 41,000 feet towards Los Angeles. The aircraft was flying on autopilot and encountered some mild atmospheric turbulence. The autopilot made numerous control inputs to maintain proper altitude, speed, heading, and so forth. As a result of certain autopilot commands, the right outboard engine failed to respond and eventually "flamed out". The captain, copilot and flight engineer directed their attention to trying to restart the failed engine. In the meantime, the autopilot was unable to keep the aircraft at the selected altitude and heading. Finally,, the aircraft slowed to the point where it rolled and pitched down into a dive, loosing 20,000 feet in less than 2 minutes. The pilot, sensing the roll and dive of the plane, tried to quickly bring the aircraft under control. Unfortunately, he was forced to determine the current state of the plane, what had gone wrong, and what controls were necessary to correct the problem. By the time he had gained this "situational awareness" as it is called, and could correct the problem, the plane was exceedingly close to the ocean deck.

These incidents are usually attributed to pilot error (in the case described, probable cause was listed as "captain's preoccupation with the inflight malfunction, and his failure to monitor properly the flight instruments"). However, the growing consensus among many in the aviation industry is that a large proportion of these accidents or near accidents are the result of a poorly designed interplay between human and automation system elements.

There have been enough problems of this sort that the airline industry has been rethinking its entire approach to automation. Many no longer feel that a replacement philosophy is the best philosophy. Some designers are now working on what they call a "pilots assistant". With the pilots assistant, the pilot always flies the plane. The pilots assistant would augment the pilot by giving cooperative support, but would not actually replace him.

There are some important lessons in these examples. First, there is the suggestion that a Total System perspective is imperative in the design process. The best way to accomplish this is by using established human factors principles and design processes (see references, especially Bailey, 1989). Usually that design process is very heavy in front-end work (defining the problem, the task, and the user population - rather than designing the system per se). The actual system design and implementation comes after this front end work, and will be directly driven by the results of the front end work. If, for example you are designing a computer aid for resource management, the first thing to accomplish is to analyze the existing system. Analyze the person doing the job, the person who is trying to figure out who to dispatch and where. Perform a complete task analysis; what is the dispatcher trying to do, what are their informational needs. What is the real and ideal input/output for the system. Are there any set procedures that they follow?

During the task analysis, you can break what the person does down into minor subtasks. At this point, a task allocation procedure is done where systematic analysis results in allocating the subtasks to be performed by either human, computer, or both. Questions to be asked include; does the person need help on all of these subtasks? Should we completely replace the person for all subtasks? Probably, the answer is "no". Because if you build a system to completely replace a person for all subtasks, the underlying message is that you don't want (or need) them doing the job.

A designer doesn't have to come to that conclusion. Find those subtasks that the person is good at, and find things that they need help with, information support and so on. Once you identify where they need help, where you can support them, design the technological components and model that total system. Specify the user characteristics and actions, the things that will be built, how each of those system components will act, how the person and system will interact, and so on. Ask, how is the technology going to affect their behavior? And ultimately, how will it affect performance of the total system?

This type of system modeling is a relatively difficult thing to do. The United States Air Force has been working on this problem for several years, but I think that it's worth trying to look at that end result.

The second point I would like to make is related to this idea of modeling the total system. And that is, I think design can be too technology driven. We think we can build an expert system to do somebody's job better - so what do we do? We build it of course. I recently heard someone say (this is somewhat paraphrased), "If a person's job can be replaced by Artificial Intelligence (AI), then it probably should be replaced". That is essentially a replacement philosophy, and I think that it is a dangerous philosophy. Such a philosophy can result in products that negatively impact the user in many ways. I will briefly mention a few of these negative effects.

To start with, we are usually giving the user a sort of black box. For expert systems, it is usually a matter of the user putting some information in and getting an answer back. The user often doesn't have any idea how the expert system works. What are the results? First, like the autopilot example, the user can have too much unfounded confidence in the system. Or on the other hand, since the user doesn't know how the system works (and it's a computer which the user may not really understand anyway), they don't have any confidence in it. They don't really trust its judgment at all. Both of these situations can end up causing problems.

Some other problems or negative effects have also occurred, for example, loss of practice. If you bring in AI or some other computer technology that is replacing the person (for example, in nuclear power plants where the user is just acting as a passive monitor), the person is not practicing doing their job, they are not being trained. Lack of practice and training ultimately results in the person loosing their skill. You may say, "Well, so what? It doesn't matter". It does matter because most expert systems are limited. There is going to come a point when the expert system fails. In the nuclear industry, there will come an accident when the expert system reaches its limits. Who will take over when that happens? The person that has been sitting around not doing the job for three years? I don't think that's what we want.

Alienation from the job has also been noted. Consider the example where the operator has essentially been replaced in the nuclear power plant. They are not doing their job, not really operating the power plant. Instead, they are just passively sitting around making sure nothing goes wrong with the computer operating system. One of the things we know from studies in Psychology is that people derive importance and a sense of identity through the work that they do. The person who has been replaced, who is just monitoring some computer, isn't doing that job anymore. This results not only in alienation, but also in a loss of self-esteem.

None of these problems have to do with how well the job is ultimately being performed, per se, but it is affecting the user. And if you affect the user, at some point it will affect the total system. It might not be until some emergency happens, but that's not when we want to find out.

I've suggested that if people are doing a job, they like doing it, want to do it, and want to learn more about it, that instead of building something that essentially replaces them, we give them a tool to help them. Talking about it in this sense is very abstract, so I've decided to create for you two different systems; a replacement system, and an augmentation "tool". I am going to do it in a rather unorthodox domain - liars poker. In order to fully appreciate the differences between these two systems, you need a working familiarity with the game of liars poker.

Liars poker is a game that you play with cards, just like regular poker. Some number of cards is dealt face down to the players. Each player looks at his/her hand, and going around the table, people start calling poker hands. Each person must beat the hand called before them. The difference between this game and conventional poker is that you are not saying that the poker hand is in your own cards. Instead, you are saying that the hand you call would be found among all the cards in everyone's hand, not just your own. If you call full house (two jacks, three queens, for example), you are saying that of all the cards in everone's hand (and showing on the table), there are at least two jacks and three queens.

As each person calls a hand, they lay down one card face up in front of them. Thus as the game progresses, more and more of the cards are laying face up on the table. However, as the game progresses, the hands being called are more and more unbelievable (especially in light of all the cards now showing on the table). The reason that it's called liars poker is because, not only do you bluff like in regular poker, but you bluff on a large scale. At some point, someone is forced into a lie that is simply beyond belief. The person following them calls this person a liar and all players show their remaining cards. If the person was, in fact, lying and the hand is not to be found in all the cards, this "liar" must pay a penalty by drinking whatever is in the glass in the center of the table (usually alcohol of some varying strength, hard-core players such as my husband use Cool Breeze or 151 rum). If the hand is to be found among the cards, the slanderous person who called the player a liar must pay a penalty by drinking the contents of the glass. However, they are redeemed slightly by being allowed to pour the contents of the next glass (very confident players tend to pour very big glasses). Depending on the crowd, this game can get pretty rough after a few hours.

It's a really fun game. When we're out there in the middle of Idaho with nothing else to do on a long winters evening, we'll find someone in town who's never played before and drag them out to the house. We live pretty far outside of town, and once you start drinking at our house, there's no way out.

So we bring people out and sit them down to play liars poker. Invariable, they get horrendously drunk. Because when you are new at liars poker, you are not really aware of all the nuances and how to play. So you tend to loose pretty frequently. Unfortunately, the more you loose, the more drunk you become. That makes you loose more, and you go into an endless spiral. We've become notorious for indoctrinating people to this game.

This seemed like a perfect testbed for an expert system or some kind of computer aid. So I asked students in my Human-Computer Interaction class, "How would you like it if you had a computer sitting right there next to you to help you play?" They said, "I don't know, what would it do?" I replied that it would be a traditional expert system. It would be a state-of-the-art expert system - it would encode and remember everything people have said, know what is on the table, and what you have in your hand (although it doesn't know what other people have in their hands). It would take all the situational input (what has been called in the past, what's in your hand, what the guy called before you, and so on) and it would tell you what card to lay on the table and what hand to call.

I described such a typical expert system to my students (who of course know how to play liars poker) and asked them to tell me, honestly, how well they would like it. Half of the students said yes, they would like it and the other half said no. At this point, I was curious as to why this mix of answers. Querying them further, I found that the people who said yes only had one goal - that was to save themselves from getting horribly drunk and having a bad hangover the next morning. They didn't care if the expert system was, in essence, just sitting there playing the game for them. As long as it kept them from getting them drunk, they were happy.

The other students said "no, I don't think I would want that." When asked why, they replied, "Well, why do you play cards? It's fun to play." They wanted to come back some other evening and be able to play on their own without an expert system. They said they wouldn't want the expert system; they would want to learn the game and didn't think that using the expert system would be a good way to learn the game.

So I started thinking, if you just wanted help, if you didn't want to be replaced in playing liars poker, what kind of form would that help take? A lot of ideas can be generated, but one place to start is to see what an expert person would do. A person would act as a coach, saying things like "the strategy I use is to just always randomly lie", or "well, on this one you have a bad hand so you should try to slow things down, how do you think you would do this?". This would lead to a short interchange. Another one you hear a lot is something like "don't worry, Sallie always lies", and so the user can build that knowledge into their strategy. The player gets some guidance but at the same time gets to do the task.

In addition to this kind of coaching, tools could take many other forms. In fact, some of these I've even seen people do for themselves, such as writing an ordered list of all the poker hands. Computer aiding can be something as simple as a memory aid, listing the poker hands, reminding you of the kinds of things people have been calling during this game, telling you the probability of the hand that was called before you, and so on. It might be some extra information, knowledge that the expert has that we don't - something like - if you have a lousy hand, you should slow things down so there are more cards to look at on the table. It's not telling you the answer, it's just giving you a piece of information.

When we are thinking in terms of our user, there are a lot of possibilities - when giving them technology, the goal should be to remain very broadminded. We must ask ourselves, what will work for this user, what's going to work for the Total System? And go from there. The thought I want to leave you with is really a philosophy or viewpoint - a human or humanity oriented viewpoint, rather than a technology oriented viewpoint. Design for the Total System. Then harness the appropriate technology that will help you serve that goal.

For more information about good resources available for engineers and system designers to gain some familiarity with human factors, contact me. (These include courses, tutorials, and conferences (which also offer one-day tutorials on a wide variety of topics)).

References

ADAMS, J.A. 1989. Human Factors Engineering. New York: Macmillan Publishing Company.

BAILEY, R.W. 1989. Human Performance Engineering: Using Human Factors/Ergonomics to Achieve Computer System Usability. Englewood Cliffs, N.J.: Prentice Hall.

BURGESS, J.H. 1986. Designing for Humans: The Human Factor in Engineering. Princeton, N.J.: Petrocelli Books.

CARROLL, J.H. (ed.) 1987. Interfacing Thought: Cognitive Aspects of Human-Computer Interaction. Cambridge, Mass: MIT Press.

LAUBER, J.K. 1987. New Technology, Human Performance and Transportation System Safety. Proceedings of the 31st Annual Meeting of the Human Factors Society.

NORMAN, D.A., AND S.W. DRAPER. (eds.). 1986. User Centered System Design: New Perspectives in Human-Computer Interaction. Hillsdale, N.J.: Lawrence Erlbaum Associates.

RASMUSSEN, J. 1986. Information Processing and Human-Machine Interaction: An Approach to Cognitive Engineering. New York: Elsevier Science Publishing Company.

RUBENSTEIN, R., AND H. HERSH. 1984. The Human Factor: Designing Computer Systems For People. Burlington, Mass: Digital Equipment Corporation.

SHNEIDERMAN, B. 1980. Software Psychology. Boston, Mass: Little, Brown and Company.

SANDERS, M.S., AND E.J. MCCORMICK. 1989. Human Factors in Engineering and Design (sixth edition). New York: McGraw-Hill Book Company.

WIENER, E.L., AND R.E. CURRY. 1980. Flight deck automation: Promises and problems. Ergonomics, 23, 995-1012.

WIENER, E.L. 1985. Human Factors of Cockpit Automation: A Field Study of Flight Crew Transition. NASA Contractor Report 177333.

The Future of Prescribed Fire: Concerns and Knowledge Needs

J. K. BROWN
Intermountain Research Station, Forest Service,
U.S. Department of Agriculture
Missoula, Montana

Abstract

An intensifying conflict between the need to use prescribed fire for managing vegetation and increasing constraints imposed by the need to maintain air quality is of major concern. Forests and grasslands continue to undergo successional change. Many forests are becoming denser and more dominated by tolerant species. Many grasslands are being encroached by shrubs and trees. As a result, some resource values are diminished and diseases and insect outbreaks are increasing. Land management publics need to know that vegetation must be managed to solve these problems and that prescribed fire is an important means to accomplish this. The increasing regulation of air quality and a growing concern about global climate change due to carbon dioxide in the atmosphere threatens the application of prescribed fire. Tradeoffs between foregoing prescribed fire and meeting stricter air quality regulations need to be described and communicated. Solutions to the conflict are discussed. Continued application of prescribed fire requires more knowledge and skill to apply fire properly and to demonstrate professional credibility. Artificial intelligence (AI), expert systems, and geographic information systems (GIS) are discussed as methods of helping organize and interpret the rapidly expanding body of technical knowledge that should be considered in applying prescribed fire. AI techniques are being applied in an expert system that assists in designing fire prescriptions, a Fire Effects Information System, and in modeling plant response to fire. Technical knowledge gaps involving estimation of fuel moisture content, fuel consumption, fire behavior, and effects of fire on long-term site productivity are discussed.

Résumé

Un conflit entre le besoin d'utiliser le brûlage dirigé pour aménager la végétation et les contraintes imposées par la nécessité d'assurer le maintien de la qualité de l'air ne cesse de s'aggraver et est fort préoccupant. La succession végétale continue de faire évoluer les forêts et les herbages. De nombreuses forêts deviennent plus denses et sont de plus en plus dominées par des essences tolérantes. De nombreux herbages sont envahis par des arbustes et des arbres. Il s'ensuit que certaines ressources perdent de la valeur et que les épidémies de maladies et les infestations d'insectes augmentent. Le public intéressé par la gestion des terres doit savoir qu'il faut aménager cette végétation pour résoudre ces problèmes et que le brûlage dirigé est un outil important pour y arriver. L'augmentation des règlements concernant la qualité de l'air et la préoccupation grandissante à l'égard des modifications du climat à l'échelle mondiale provoquées par le dioxyde de carbone dans l'atmosphère menace le recours au brûlage dirigé. Il faut trouver des compromis entre l'interdiction du brûlage dirigé et le respect des règlements plus sévères sur la qualité de l'air les décrire et les faire connaître. Les solutions à ce conflit sont examinées. La poursuite du brûlage dirigé exige l'acquisition d'un plus grand nombre de connaissances et de compétences en matière d'utilisation adéquate du feu et afin de faire la preuve d'une crédibilité professionnelle. L'intelligence artificielle, les systèmes experts et les systèmes d'information géographique SIG sont les méthodes examinées pour aider à organiser et à interpréter la masse rapidement et sans cesse croissante de connaissances techniques dont il faudrait tenir compte lors du recours au brûlage dirigé. Les techniques d'intelligence artificielle sont mises en application dans un système expert pour aider à élaborer des prescriptions sur le brûlage dirigé et un système d'information sur les effets du feu et à modéliser la réaction de la végétation au feu. Le manque de connaissances techniques sur l'estimation de la teneur en humidité du combustible, la consumation de combustible, le comportement du feu et les effets du feu sur la productivité à long terme de l'emplacement est examiné.

Introduction

The future of prescribed fire is certainly a timely topic because constraints or restrictions on the use of fire seem to be on a collision course with a growing awareness of the need to manage vegetation using prescribed fire. On the one hand, the dynamic nature of vegetation requires management to provide commodity as well as noncommodity resources and to protect against damage from wildfire. For this, fire and other silvicultural treatments are an essential means of management. On the other hand, increasing concern about air quality and a potentially new related problem, global warming, is leading to more restrictions on use of fire. A steadily increasing technical world is also changing the way land managers do

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

business and pressuring for a more highly educated fire manager.

We must seek answers to questions such as: What actions can managers take to assure that prescribed fire remains a viable means of managing vegetation and ultimately resources? How can new technology help? What advances in research are needed? How do we deal with information overload? In this paper, concerns and technology related to these questions are discussed.

Natural Area Fire

In the summer of 1988, severe drought coupled with unusually strong winds led to 1.5 million ha burned in the western United States plus another 0.8 million ha in Alaska. Approximately 570,000 ha burned in Yellowstone National Park and the surrounding National Forests. Over half of the burned area occurred in parks and wildernesses under a policy allowing some naturally ignited fires to burn. Some fires escaped boundaries, burned across ranchlands, threatened villages, and destroyed property.

The fire activity received extensive media coverage. It triggered public debate and professional concern about Federal fire management policies. Agency reviews and Congressional hearings were held to determine whether new fire management direction is needed particularly regarding natural fire policies. Thus, the question of how to manage fire in parks, wildernesses, and other natural areas is a major concern.

How should fire in parks and wildernesses be managed? As a result of the extreme fire situation in 1988, a fire management policy review team was appointed by the U.S. Secretaries of Agriculture and Interior to address this question. They made a number of recommendations to modify existing fire policy and its implementation in National Parks and wildernesses. First, they recommended that prescribed natural fire policies in the agencies be reaffirmed and strengthened. This reaffirmation is based on the knowledge that exclusion of fire leads to unnatural changes in vegetation and wildlife, which violates the objectives of park and wilderness management. Fire exclusion also allows accumulation of fuels that can lead to uncontrollable, damaging wildfire. I will also add that in spite of modern firefighting technology it is impossible to exclude fire over the long term.

A number of other recommendations deal with the obvious need to do a better job of managing naturally occurring fires. These include preparation of technically stronger prescriptions and additional decision criteria on when to allow fires to burn, better assurance that adequate resources are available to ensure prescribed fires will remain within prescription, use of planned ignitions to reduce hazardous fuels, increased opportunities for public involvement, and coordination with local communities, and more training to carry out these programs. Clearly, we need to work toward a more competent, professional approach to managing fire in parks and wildernesses. Additional research is certainly needed to support this effort particularly in developing better prescriptions and providing a technical basis for deciding when to allow fires to burn.

Two major improvements in technology and its application appear essential to managing fire in these areas: (1) the influence of drought must be more clearly understood and incorporated in prescriptions, and (2) planned ignition prescribed fires should be utilized to a greater extent to reduce hazard in critical areas such as boundaries and to mimic natural fire processes. Some of the unacceptable fire during 1988 could have been avoided if more definitive knowledge of drought had been available to prescribed fire decision makers. Early summer fires could have been suppressed. Later in the summer they could have been reignited if prescription conditions had been met.

In the United States, use of planned ignitions in parks and wildernesses is a debated issue and suffers from lack of funding. Planned ignitions have been used to a considerable extent in some National Parks and small grassland natural areas. But, in National Forest wildernesses and some National Parks, planned ignitions are not used to any significant extent partly because of concern about being unnatural and conforming to fire policy. Forest Service fire policy allows planned ignitions only to reduce unnatural fuels if necessary to permit lightning to play a natural role or to reduce risks of fires escaping across wilderness boundaries.

Perhaps, the conservative view toward allowing only lightning fires to burn in wildernesses has been appropriate for the early stages of a natural fire program. However, it is time for planned ignitions to "step forward" and be recognized as essential to natural fire programs. In large wildernesses and parks, planned ignitions should be used regularly to reduce threats of fire to property values and natural area boundaries in support of a program allowing lightning fires to burn. In small wilderness areas, parks, and natural areas, planned ignition prescribed fires are the only realistic approach to mimicking natural fire effects. Natural fire regimes have nearly been eliminated because of the suppression of fires on adjoining lands that historically spread into the small natural areas.

The debate over natural fire may continue for some time on a philosophical basis. Technically, however, a reasonable scientific basis exists on which to carry out planned ignition prescribed fires to mimic natural fires. The historical frequency and intensity of fires is documented in a number of studies for different vegetation types (Kilgore 1987). Quantitative information about the pattern of fire or the postburn vegetation mosaic is limited. However, nature appears to have provided considerable variability in fire effects. Thus, a wide latitude exists for mimicking natural fire. More knowledge of natural fire patterns would be helpful to natural area managers, but it should not constitute a major hurdle to use of planned ignitions.

If the goal of natural area management is focused on creating vegetation patterns that could result from wildfires, then planned ignition prescribed fires can be used with strong technical justification.

In parks and wilderness areas of Canada, whether or not man-caused ignitions are natural is not an important issue. Van Wagner's (1985) convincing view that natural fire regimes should be managed by concentrating on fire's effect rather than its cause seems to prevail. Park policies allow planned ignition prescribed fires if they are needed to meet fire management objectives. The challenge is to identify the composition and structure of vegetation that satisfies the ecological goals of individual parks. Then an appropriate strategy for ignitions can be determined, which may involve planned and unplanned ignitions.

A challenging application of planned ignitions is to conduct large scale prescribed fires in forests such as lodgepole pine (Pinus contorta) where large woody fuels and understory conifers are important fuels. For example, in parks and wilderness areas of western Canada and the United States, the vast areas of lodgepole pine and associated fir and spruce are now being managed or could be managed under a natural fire policy. The extensive, uncontrollable fires in the Greater Yellowstone Area were predominately in lodgepole pine. Threats to villages and boundaries could have been greatly reduced if a program of prescribed fire and cultural treatment had been directed toward critically located fuels during the preceding decade or two (Brown 1989).

The feasibility of such a program, which involves severe burning conditions including crown fire behavior, needs to be studied operationally to determine workable prescriptions, ignition methods, logistics, and costs. High intensity prescribed fires in lodgepole pine are possible. For example, most of the conifers were killed by prescribed burning of old growth spruce, fir, and lodgepole pine in Colorado to control mistletoe disease and improve bighorn sheep habitat (Simmerman and Fischer in press). In Canada, stand replacement fires have been successfully conducted in lodgepole pine and jack pine (Pinus banksiana). However, it was difficult to achieve crown fires (communication with Dennis Quintilio). A skilled and experienced interagency cadre may be required to help individual parks and wildernesses plan and conduct prescribed fires. Perhaps Canadians and Americans could join in this cadre and share in its assistance to natural fire programs.

Vegetation Management

Forest and rangeland vegetation is constantly changing with and without manipulation by managers. Vegetational succession is an ongoing process. The slow but ever-changing nature of vegetation requires a long-term view to obtain the most benefit from our resources. Successional advancement creates many problems that require active management including prescribed fire and other cultural practices. But such management is not happening in many wildland areas, particularly where extensive forestry is practiced. The dynamic nature of forest and rangeland vegetation is sneaking up on our capability to manage resources properly.

The age distribution of marginally commercial and noncommercial forests is shifting to that of older stands. Fire that historically triggered successional changes has been reduced on the landscape. And in many forests we have not compensated for the lack of fire by using harvesting and other cultural methods. Species composition is shifting to that of later successional stages. Tolerant tree species are increasing due to absence of fire and to selective harvesting practices that preferentially remove intolerant species. Woody plants are invading grasslands.

As forests become overstocked, sometimes overmature, and successionally ready for change, insects and diseases find conditions to their liking. Outbreaks of insects and occurrence of root disease appear to be worsening (Stewart 1988). Evidence indicates that polluted air and climatic changes are stressing forests, which in turn affects their susceptibility to insect and disease attack. Fuels are accumulating from these successional processes. Mortality from insects, disease, weather, tree suppression, and other factors is contributing dead biomass to the surface fuels. Thickening of understories is increasing crown fire potentials by creating live ladder fuels.

Some examples illustrate these concerns. In ponderosa pine (pinus ponderosa) stands where it is a seral species, more tolerant conifers such as Douglas-fir (Pseudotsuga menziesii) and grand fir (Abies grandis) in the Northern Rocky Mountains (Arno 1988) and white fir (Abies concolor) and incense cedar (Libocedrus decurrens) in the California Sierra Nevada (Rice 1987) are filling in the understories. Overstories consist mostly of old ponderosa pine, but often the pine are absent due to selective harvesting. In some cases, no cone bearing ponderosa pine remain. A strong shift in species composition has occurred. The fir, often overstocked, are being repeatedly defoliated by western spruce budworm (Choristoneura occidentalis) and tussock moth (Orgyia pseudotsuga). Timber productivity is reduced. The potential for high intensity fire has increased due to the thickened understories. Because people are attracted to this forest zone, an enormous number of dwellings have been built in hazardous fuel situations. Harvesting and fire are often eliminated in forest home areas allowing succession to proceed unchecked. Consequently, almost yearly somewhere in the Western United States, homes are destroyed by wildfire in this forest type. A similar problem exists where ponderosa pine is climax, but here, the understory consists of dense patches of ponderosa pine and sometimes Gambel oak (Quercus gambelii).

In many jack pine forests, the more tolerant balsam fir (Abies balsamea) is gradually assuming dominance. Jack pine either deteriorates naturally with age or is harvested. In many areas of Canada, balsam fir is not a commercial species and remains on the site after a harvest. As balsam increases, eastern spruce budworm Choristoneura fumiferana) outbreaks become more severe. Productivity declines and accumulating dead fuels increase the likelihood of high intensity wildfire.

In parks, wildernesses, and other noncommercial forests of the Western United States and Canada, succession in lodgepole pine is proceeding at different rates depending on longevity, which can range from 100 to over 400 years (Brown 1975). Once lodgepole pines reach approximately 20 cm diameter at breast height they become highly susceptible to mortality by mountain pine beetle (Dendrotonus ponderosae) (Cole and Amman 1980). Mortality can be widespread following periodic outbreaks. Today, in many stands the potential for high intensity wildfire is increasing due to buildup of fallen dead trees and expansion of spruce and fir in the understory. High intensity wildfire can be expected in this type as evidenced during 1988 over extensive areas of Yellowstone National Park and the surrounding National Forests.

Quaking aspen (Populus tremuloides) faces a different problem in noncommercial forests of the Western United States. In the absence of fire, the aspen is slowly being lost. Aspen is seral on a majority of sites and is eventually replaced by conifers (Mueggler 1976), which results in reduced forage for wildlife and livestock and reduced water yield (Brown and Simmerman 1986). The reverse successional problem occurs in the parklands of Alberta where aspen encroaches upon valuable grasslands. Maintaining the grassland resource requires periodic fire (Bailey and Anderson 1979). Millions of hectares of grasslands have experienced a dramatic encroachment of woody vegetation (Gruell 1985). For example, juniper (Juniperus spp.), Douglas-fir, ponderosa pine, limber pine (Pinus flexilis), and lodgepole pine have invaded western grasslands resulting in a marked reduction of palatable forage (Gruell et al. 1986). The invading trees are usually of poor form and stature for timber production. Similarly, oak and other hardwoods have encroached on prairies of the Midwest.

In all of these examples, prescribed fire is an important means of providing desirable resources and reducing hazardous fuels and threats from wildfire. Demand for nonconsumptive uses of forested lands is increasing. For example, private wildlife advocacy organizations have contributed many thousands of dollars on a cost sharing basis with the U.S. Forest Service to manage wildlife habitat using prescribed fire. Nonconsumptive uses of the forest are often viewed by the public as not compatible with harvesting for wood products. This puts even more reliance on prescribed fire to meet resource demands.

Traditional uses of prescribed fire for site preparation and hazard reduction following harvesting remain important for managing timber resources. Additionally, where harvesting is not possible, the need to manage successional processes using prescribed fire is becoming increasingly apparent. At the same time, constraints are being imposed on managers to curtail smoke pollution and restrict harvesting methods to satisfy esthetic demands. This emerging conflict must be resolved by working with the interested public or critical users to develop an understanding of successional processes and the tradeoffs between constraints on management practices and resource benefits. Alternatives for managing vegetation must be thoroughly evaluated and compared, often with public involvement, to determine the best approach for meeting resource goals.

Air Quality

A major concern is that the increasing regulation of smoke pollution will continue to threaten the application of prescribed fire. Reasons for concern in the United States and solutions to the problem were described well by Dennis Haddow (talk at Symposium on Wildland Fire 2000, Lake Tahoe, CA, 27-30, April 1987). These concerns include tightening of regulations such as possible adoption of a 2.5 micron particulate standard, elimination of the rural fugitive dust policy causing more concern for particulate in rural areas, growing interest in maintaining visibility and regulating haze, better means of identifying source of pollutants, concern over air toxics in general, and increased populations and industrial growth. Some of these reasons for concern apply in Canada as well. For example, interests in recreation, tourism, and retirement communities are demanding clean air.

Managers and environmentally oriented publics are increasingly aware of the need to use prescribed fire in resource management. Solutions to the conflict between clean air and prescribed fire must be sought by managers and an informed citizenry through cooperation and understanding of the problems. Land managers must cooperate in efforts to regulate and improve air quality so that those efforts remain reasonable. They must actively seek involvement in regulatory efforts, otherwise their inaction will give away the capability to use prescribed fire (Haddow in press). As Haddow pointed out, whoever writes the rules determines how the game is played.

Dealing with this conflict also requires that land managers maintain professional credibility in applying prescribed fire. Technical competence must be demonstrated by using state-of-the-art technology. Because credibility is a matter of perception, thus we need to demonstrate our skill in applying technology in the planning and conducting phases of prescribed fire.

We should attempt to reduce emissions by reducing the amount of fuel consumed when consistent with prescribed fire objectives. For example, consumption is reduced through increased utilization and burning when large woody fuel moisture is high. Smoke is reduced by isolating fuels such as rotten logs that will smolder for long periods. Range and wildlife improvement will result from the use of spring burns when possible and from minimizing consumption of woody plants. Decisions to use prescribed fire must be technically sound to avoid unnecessary burning and smoke.

We need to continually work at developing a public awareness of the ecology of forest and grassland resources including the natural role of fire. The public understands the need for good air quality better than they understand the need for prescribed fire (Haddow in press). Round one--to establish that fire is a natural factor--is well along. Major changes in fire policy have occurred in the past 15 years. But round two--to establish the significance of fire in managing diverse resources--is just beginning. The public needs to understand the costs and consequences of managing vegetation using prescribed fire and other alternatives including the alternative of do nothing. In many vegetation types, this alternative eventually results in an accumulation of fuels, and ultimately a severe wildfire that releases excessive amounts of smoke.

Research must also be undertaken to help resolve this conflict. Better knowledge of emission production, combustion efficiency, and smoke management techniques is needed to deal with regulatory agencies scientifically rather than emotionally. Better understanding of nutrient and carbon cycling is needed to evaluate the role of fire in forest productivity. We need to increase our knowledge of the fire treatment and minimum fuel consumption required to meet various resource management objectives.

Global Warming

Increased carbon dioxide and other air pollutants in the atmosphere are expected to raise the temperature of the earth's lower atmosphere by 1.5 to 4.5°C during the next century, more than during the past three warm epochs (Budyko and MacCracken 1987). Although considerable uncertainty remains about regional climate changes, the continental United States may suffer more frequent drought conditions (Rodenhuis 1989).

What are the implications of these possible changes? Because prescribed fires release carbon dioxide into the atmosphere, the growing concern for carbon dioxide in the atmosphere could lead to public pressure to reduce prescribed burning. The extensive cut and burn activity in South America is certainly disturbing and is receiving attention in the scientific media. The critical problem, however, is extensive loss of tropical forest and not the use of fires to clean up slash.

Concerned citizens need knowledge of the carbon cycle including photosynthesis, respiration, decay, and fire. Respiration, decay, and fire all produce carbon dioxide. Eliminating prescribed fires from this process would not appear to have a significant effect. Over time, decay and microbial respiration would approximately make up reductions in carbon dioxide due to elimination of prescribed fire. Effort may be needed to quantify the role of fire in the carbon cycle.

Another concern of direct importance to land managers is whether existing knowledge of fire effects will hold true in new environments. For example, how will vegetation respond to fire in new environments that, in some regions, will probably be stressed due to climatic change? Will existing empirical relationships that predict postfire composition, cover, and yields apply in new environments? Changing climate and related vegetation and fuels can be expected to alter the frequency, intensity, and pattern of fires in some regions. Our predictions of fire effects will become more tentative and require new approaches. More fundamental fire effects relationships will be needed to answer questions about response to fire in changing environments.

Knowledge Management

The growing body of technical knowledge is overwhelming in all fields. Even the specialist land manager is overwhelmed. To write a fire prescription, a diversity of information is required dealing with effects of fire on vegetation, soil, wildlife, water, and resource outputs; fire behavior under an array of weather conditions and ignition techniques; weather probabilities; and logistical alternatives. Technical information can be found in various publications, computer programs, and the minds of experts. I believe a major concern lies with developing effective ways of assimilating technical knowledge for practicing land managers.

Information alone does not provide knowledge. As J. Naisbitt pointed out in his book Mega Trends, "We are drowning in information but starved for knowledge." We need methods to help interpret data and select appropriate information from an enormous supply. The computer is an obvious means to help solve this problem. However, it too can contribute to confusion by providing outputs that are complicated and hard to understand, too little or too much information, and incorrect information. Development of computer programs for transferring knowledge to managers must be done with an understanding of the applications of that knowledge and the detail needed.

Two emerging computer applications that can help turn information into knowledge are expert systems and geographical information systems (GIS). Expert systems can be defined as computer programs that offer solutions to complex problems by mimicking human reasoning processes and employing a knowledge base of information extracted from human experts (Stone et al. 1986). Essentially, expert systems are new computer techniques that allow users to more effectively apply a body of knowledge. In natural resource management, their development involves forming and using rules about ecological phenomenon and management practices. However, the formalization of these rules forces clearer thinking about processes and relationships, and the linking of many rules goes beyond what the human mind can quickly comprehend.

In prescribed burning, expert systems could be used by managers to help select and interpret predictive equations. For example, suitable equations for predicting duff moisture content could be suggested to a user. Advice might be offered that the predictions are probably low in dense stands that protect the forest floor from sun and wind. Knowledge of threshold conditions to achieve fire spread could be captured from experienced prescribed burners. Fire prescriptions could be tailored more closely to resource and fire objectives. Expected plant response over short and long periods could be related to fires at different seasons and of varying severity. Much knowledge of succession could be effectively transferred to land managers through expert systems. To help in preparing fire prescriptions, Reinhardt (1987) has developed a prototype expert system that helps users determine prescription conditions linked to resource objectives. The interactive system helps set specific objectives for the fire, quantify constraints on what the fire should not do, determine the appropriate fire intensity, and determine the appropriate time of year, fuel moisture contents, and wind speed. Existing algorithms for predicting fuel consumption, fire intensity, and tree mortality are employed together with rules that access and link the algorithms and attempt to fill in gaps where algorithms do not exist. In this system, the user consults the latest technology but can override suggested results at any point with other preferred information. Working through the process is as important as the answer. This allows the user to understand the linkages between objectives for the fire and the prescription. The system allows users to quickly consider "what ifs." For example, what if constraints on the fire effects were changed, how would this alter the fire prescription?

Although expert systems are probably best used for transferring technology, they may help with scientific endeavors. In modeling of ecological processes such as postfire development of plant communities, expert systems could be used to model fundamental relationships and processes with a set of rules. Models of plant response to fire could be built using rules based on regenerative mechanisms (Noble 1987). If we are forced to rethink the nature of ecological relationships, then expert systems have helped scientifically.

Expert systems are not panaceas for all of our problems (Rauscher 1987). Pitfalls exist. Expert systems cannot reason from analogy nor learn from experience, they lack common sense, and their performance deteriorates rapidly beyond their domain. Validation of expert systems can be difficult. Expert systems often require considerable work, not on the computer programming, but on understanding the problem, gathering knowledge, and formulating the rules. They have an exciting role in natural resources but will require substantial development and testing effort.

Artificial intelligence techniques not involving expert system technology can be useful for managing knowledge. For example, a Fire Effects Information System was developed to store and retrieve state-of-knowledge information about immediate and long-term fire effects on plant species, plant communities, and animal species (Fischer 1987, Fischer and Wright 1987). The easy-to-use system also contains information about species distribution, botanical and ecological characteristics, and resource management considerations. The system is expected to have interdisciplinary application in State and Federal land management agencies.

Although GIS technology has existed for some time, only recently has it been widely applied in the United States. The U.S. Forest Service is making a major commitment to implementation of GIS that will have a profound effect on characterization of land and resources. It allows knowledge and data about resources to be visualized over the landscape.

A major application involving fire effects will be the display of vegetational responses to fire. Long-term successional trends could be projected. Effects of fires of varying severity could be viewed in planning prescribed fires for many purposes. It may be particularly helpful for assessing the consequences of natural fire programs. Postfire rehabilitation needs could be assessed by overlaying predicted vegetation with topography and soil data. Considerable research remains to develop the relationships for predicting plant response and to formulate relationships for GIS application. Expert system techniques may help considerably with this task.

Computer systems offer an exciting and interesting approach to manage our growing information problem and, we hope to reduce information overload. However, computer systems can never replace the need for first-hand observation of what is happening on the land. We must avoid becoming a profession of office potatoes to keep check on the reality of computer information.

Knowledge Gaps

A final concern is that research efforts acquire new knowledge for planning and conducting prescribed fires. Several technical areas merit mentioning because of their importance to prescribed burning.

FUEL MOISTURE

More site-specific and easier-to-use methods of estimating and predicting fuel moisture content are needed. Fuel moisture is probably the most important variable to assess in planning prescribed fires because it controls fire behavior and consumption of organic matter. Controlling consumption through the fire prescription will become increasingly important because of the need to manage dead organic material. Concerns over smoke, nutrient regimes, and seedbed preparation will require managers to prepare more specific fire prescriptions.

Better knowledge of local weather and site factors affecting the drying environment will be needed to utilize predictive relationships. Moisture relationships based on physical principles but adjustable for local site conditions offers the most accuracy and precision. Empirical relationships or adjustments to physical models will be necessary long into the future because of the many local factors that influence drying.

FIRE BEHAVIOR

In the United States, most fire behavior research has been directed at rate of spread and intensity of surface fires with emphasis on predicting fire behavior for fire suppression planning. The marginal fire has received comparatively little attention. For prescribed fire planning, predictive knowledge is needed on wi[illegible] fires will spread. Identifying the marginal conditi[illegible] is critical for selecting good opportunities for burning and in preparing prescriptions. At the other extreme, prescribed burning programs utilizing mass ignition would benefit from a better understanding of conditions leading to fire whirls and other violent fire behavior. Prediction of many important fire effects at and below the ground level depends on duration of the fire and heat properties of the soil. Only limited research efforts have been directed at this problem. The role of duff as a fuel and as an insulator needs to be quantified in an effort to develop models of soil heating. Knowing time-temperature profile in the soil associated with fire characteristics and preburn conditions will permit modeling of fire effects such as plant mortality due to root injury, vegetative response from below ground perenniating organs, and soil organic matter content. This may also help in assessing long-term effects on site productivity.

FUEL CONSUMPTION AND SMOKE

Relationships for predicting live and dead fuel consumption are inadequate for many areas and vegetation types. Although a growing number of studies have reported on duff consumption, relationships contain different independent variables and apply to specific forest types. Thus, their application is restricted. A unified approach to prediction is lacking. Little knowledge exists to predict live fuel consumption, which is becoming more important for evaluating smoke impacts from rangeland burning.

To develop technically sound and publicly supportable policies for managing smoke, research is needed to determine particulate emission rate and air toxic emissions from various fuel types and prescribed fire conditions. Better smoke management techniques are needed to minimize the amount of smoke and its impact on sensitive areas.

LONG-TERM PRODUCTIVITY

The fact that fire is a natural process that triggers new successional processes seems to be widely known by natural resource professionals. However, our knowledge of long-term processes in the soil and related vegetation response is sketchy. Knowledge of fire's effect on nutrient cycling and on its role as a decomposer in the carbon cycle consists of fragmented studies primarily over short periods. We need quantification of long-term effects of fire on nutrient regimes and related composition and structure of vegetation. Productivity should be viewed not only in terms of soil nutrients but as the capacity of the land to produce desirable resources on a sustained basis.

In conclusion, the application of prescribed fire faces a growing conflict between constraints due to pollution from smoke and an increasing awareness of the need to manage some resources using prescribed fire. To resolve the conflict, we must communicate to administrators and concerned publics the importance of fire for managing vegetation that in many situations is becoming less productive. Prescribed burning must be based on the best technology available. Land managers must take advantage of new knowledge about fire and its effects together with new computer applications to help maintain skills and professionalism in applying prescribed fire. Prescribed fire offers an effective means of meeting many resource needs including parks and wildernesses, but its future application will require more than business as usual.

References

ARNO, S.F. 1988. Fire as an ecological factor in ponderosa pine forests. P. 133-139. In Ponderosa pine: the species and its management. Symp. Proc. Spokane, WA, Sept. 29-30, 1987. Wash. State Univ. Cooperative Extension Service, Pullman.

BAILEY, A.W. and H.G. ANDERSON. 1979. Brush control on sandy rangelands in Central Alberta. J. Range Mgt. 32(1): 29-32.

BROWN, J.K. 1975. Fire cycles and community dynamics in lodgepole pine forests. P. 429-456. In D.M. Baumgartner, ed., Management of lodgepole pine ecosystems: Symp. Proc. Pullman, WA, Oct. 9-11, 1973. Wash. State Univ. Cooperative Extension Service. Pullman.

BROWN, J.K. 1989. Could the 1988 fires in Yellowstone have been avoided with a program of prescribed burning? Unpublished paper presented at Am. Assoc. for Advancement of Sci. Annual Meeting, Jan. 14-19, 1989, San Francisco, CA.

BROWN, J.K., and D.G. SIMMERMAN. 1986. Appraising fuels and flammability in western aspen: a prescribed fire guide. USDA For. Serv. Gen. Tech. Rep. INT-205. Intermt. Res. Sta.

BUDYKO, M.I. and M.C. MACCRACKEN. 1987. US-USSR meeting of experts on causes of recent climate change. Bull. Amer. Met. Soc. 68(3): 237-243.

COLE, W.E. and G.D. AMMAN. 1980. Mountain pine beetle dynamics in lodgepole pine forests Part I: course of an infestation. USDA For. Serv. Gen. Tech. Rep. INT-89. Intermt. Res. Sta.

FISCHER, W.C. 1987. The fire effects information system. P. 128-135 In J.B. Davis and R.E. Martin, coords., Wildland Fire 2000, Symp. Proc. Apr. 27-30, 1987, South Lake Tahoe, CA. USDA For. Serv. Gen. Tech. Rep. PSW-101.

FISCHER, W.C., and A.H. WRIGHT. 1987. FIRESYS: using artificial intelligence techniques to build a fire effects information system. The Compiler. 5(5): 28-35.

GRUELL, G.E. 1985. Fire on the early western landscape: an annotated record of wildland fires 1776-1900. Northwest Sci. 59(2): 97-107.

GRUELL, G.E., J.K. BROWN, and C.L. BUSHEY. 1986. Prescribed fire opportunities in grasslands invaded by Douglas-fir: state-of-the-art guidelines. USDA For. Serv. Gen. Tech. Rep. INT-198. Intermt. Res. Sta.

HADDOW, D. [In press]. Working together to improve air quality and also retain use of prescribed fire. In The burning decision: regional perspectives on slash, Symp. Proc. Seattle, WA, Apr. 5-7, 1988, Institute of Forest Resources Contribution No. 66, Univ. of WA, Seattle.

KILGORE, B.M. 1987. The role of fire in wilderness: a state-of-knowledge review. P. 70-103 In R.C. Lucas, compiler, Proc. National Wilderness Research Conf.: Issues, State-of-Knowledge, Future Directions, Fort Collins, CO, July 23-26, 1985. USDA For. Serv. Gen. Tech.Rep. INT-220. Intermt. Res. Sta.

MUEGGLER, W.F. 1976. Type variability and succession in Rocky Mountain aspen. P. 16-19 In Proc. utilization and marketing as tools for aspen management in the Rocky Mountains Symposium. USDA For. Serv. Gen. Tech. Rep. RM-29. Rocky Mtn. For. and Range Exp. Sta.

NOBLE, I.R. 1987. The role of expert systems in vegetation science. Vegetation. 69: 115-121.

RAUSCHER, M.H. 1987. Expert systems for natural resource management. Compiler. 5(5): 19-27.

REINHARDT, E. 1987. An expert system for describing fire prescriptions. P. 223-225 In J.B. Davis and R.E. Martin, coords., Wildland Fire 2000, April 27-30, 1987, South Lake Tahoe, CA. USDA For. Serv. Gen. Tech. Rep. PSW-101.

RICE, C.L. 1987. What will the future wildlands be like in the year 2000...future perfect or future imperfect. P. 26-31 In J.B. Davis, and R.E. Martin, coords., Wildland Fire 2000, April 27-30, 1987, South Lake Tahoe, CA. USDA For. Serv. Gen. Tech. Rep. PSW-101.

RODENHUIS, D.R. 1989. Drought monitoring and approaches to prediction. Unpublished paper presented at Am. Assoc. for Advancement of Sci. Annual Meeting, Jan. 14-19, 1989. San Francisco, CA.

SIMMERMAN, D.G., and W.C. FISCHER. [In press]. Prescribed fire practices in in the Interior West: A survey. In The art and science of fire management, Proc. of First Annual Meeting and Workshop of the Interior West Fire Council, Oct. 24-27, 1988. Kananaskis Country, Alberta, Canada.

STEWART, J.L. 1988. Forest insects and disease research: what is needed. Presentation to Western Forestry and Conservation Association Pest Committee. Dec. 5, 1988. Seattle, WA.

STONE, N.D., R.N. COULSON, R.E. FRISBIE, and D.K. LOH. 1986. Expert systems in entomology: three approaches to problem solving. Bull. of the Entomological Society of America. 32: 161-166.

VAN WAGNER, C.E. 1985. Does nature really care who starts the fire? P. 98-100 In J.E. Lotan, B.M. Kilgore, W.C. Fischer, and R.W. Mutch, coords., Proceedings--Symposium and workshop on wilderness fire, Missoula, MT, Nov. 15-18, 1983. USDA For. Serv. Gen. Tech. Rep. INT-182.

Prescribed Burning in Canada: Progress and Problems

P.C. WARD
Ontario Ministry of Natural Resources
Sault Ste. Marie, Ontario

Abstract

The use of prescribed burning has expanded significantly in Canada in recent years. Driven by the need to enhance their forest regeneration efforts, provinces with established burning programs have increased the number of burns and the area treated by prescribed fire. Other agencies which previously did little or no prescribed burning have moved to develop their capabilities and implement an annual burning program. New technologies have played a key role in this expansion. The helitorch aerial ignition system is in widespread use, providing faster and more sustained ignition in a variety of fuel types. Improved fire behaviour prediction is now available, through the use of better fuel sampling techniques and the development of the Canadian Forest Fire Behaviour Prediction System. Other innovations are in use, such as portable minisondes for on-site upper air observations.

Changing technologies can also have a negative impact. Ontario has experienced cases of unexpected severe fire behaviour, including fire whirlwinds, on helitorch-ignited burns. Widespread conversion to full-tree logging systems is resulting in large roadside accumulations of slash, but significantly less fuel loading in cutovers. These situations require continuing development and improvement of burning techniques. The most serious challenge to Canadian prescribed burning programs may be the increasing public and regulatory concern about environmental impacts and air quality. Continuing research and responsive program management will be required to maintain prescribed burning as a viable fire and forest management technique.

Résumé

Depuis quelques années, on a de plus en plus recours au brûlage dirigé au Canada. Motivées par la nécessité d'améliorer leurs efforts en matière de régénération forestière, les provinces déjà dotées de programmes de brûlage ont augmenté le nombre de brûlis et de surfaces traitées par brûlage dirigé. D'autres aginces qui avaient très peu ou aucunement recours au brûlage dirigé ont décidé de se doter de cet outil et mis en oeuvre des programmes annuels. De nouvelles tehnologies ont joué un rôle clé dans l'élargissement des activités de brûlage dirigé. L'hélitorche, un dispositif d'allumage aérien, est maintenant largement utilisée car elle permet d'allumer plus rapidement et plus uniformément une variété de types de combustibles. On peut maintenant mieux prédire le comportement du feu grâce à l'utilisation de meilleures techniques d'échantillonnage du combustible et à l'élaboration de la Méthode canadienne de prévision du comportement des incendies de forêt. D'autres nouveautés sont utilisées, comme les minisondes portatives qui permettent d'effectuer sur le terrain des observations en altitude.

L'évolution des technologies peut également avoir un impact négatif. L'Ontario s'est retrouvée aux prises avec des cas de comportement grave et imprévu du feu, y compris des tourbillons de feu dans des brûlis enflammés par hélitorche. L'adoption à grande échelle de la méthode d'exploitation par arbres entiers entraîne l'accumulation d'une quantité importante de débris en bordure de la route mais d'une biomasse de combustible beaucoup moins importante dans les parterres de coupe. Ces situations exigeront l'élaboration et l'amélioration en permanence des techniques de brûlage. La préoccupation grandissante du public et des organismes de réglementation à l'égard de l'impact sur l'environnment et de la qualité de l'air peut être l'obstacle le plus important des programmes canadiens de brûlage dirigé. Il faudra poursuivre les recherches et pratiquer une gestion de programme judicieuse pour que le brûlage dirigé reste un outil d'aménagement forestier rentable.

Introduction

Having spent the past eighteen months or so serving on the organizing committee for this conference, I find it very gratifying to stand in this room today and to see the results of those efforts all falling into place. When we started to work on this conference a year and a half ago, our committee gave considerable thought to developing a conference theme. We wanted something topical, but also of lasting interest, and something of relevance to all of the disciplines represented here.

The theme we chose - fire and forest meteorology in a changing environment - really took shape rather quickly. Despite the varied backgrounds of the committee members, we were all familiar with the challenges of coping with a changing environment - both our physical environment and a changing social and economic environment.

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

We also saw from personal experiences the impacts of new technology on our areas of endeavour, and the new concerns that are arising: the questions about what we do, and how we do it. These concerns come both from within our own organizations, and from the outside: our clients, our cooperators, our peers, and the public.

During those discussions, I used prescribed burning as an example of an endeavour where new technologies had significantly improved the way we deliver a particular fire management program, but where changing conditions and concerns require continuing review of the use of prescribed fire. I also feel that a continuing research and development effort will be needed to maintain prescribed burning (PB) as a viable management tool.

I don't claim to be a national expert on prescribed burning in Canada; nor am I a provincial expert on prescribed burning in Ontario. But I have spent most of the past decade working on the evaluation, development and transfer of new technologies in the fire management program in Ontario. Many of these efforts have been applied to prescribed burning, or have had spin-off effects on the prescribed burning program.

In this address I'd like to consider the impacts of new technologies on prescribed burning, and the challenges fire managers may face as their operating environment evolves. I have tried to approach this subject from a national perspective, but I will draw many examples from our experiences in Ontario, which is, I must confess, the place I know best.

Significant strides have been made in Canadian prescribed burning programs in the past ten years. The number of provinces using prescribed fire has increased. Quebec and Newfoundland, for example, have recently made efforts to further develop and enhance their burning programs through technology and training exchanges with other provinces. The Canadian Parks Service is using more prescribed fire in its management of our national parks. British Columbia, Alberta and Ontario, which already had significant burning programs, have increased their number of burns. The total area treated annually and the average size of individual burns has increased. Burning is being carried out in a diversity of fuel types and conditions, and for diverse purposes. For example, in Ontario we have a regular burning program to maintain a remnant tall-grass prairie ecosystem located within the city of Windsor. Plans are in place for a stand conversion burn in a provincial park in southern Ontario to convert pine plantations to the natural oak-savannah ecosystem. We've done winter marsh burning for wildlife and vegetation management, as well as increasing amounts of cutover burning for forest regeneration and wildlife habitat.

Much of that program expansion has been fueled by new technologies. In the 1970's, burning programs were often restricted by ignition techniques. In Ontario, we frequently used hand ignition, which posed safety problems, as well as imposing a limit on the size of burns that could be feasibly ignited during a single burning period. We also used the Ontario Aerial Ignition Device (AID), or ping-pong ball machine, which was most effective on conventionally harvested sites with a good supply of well-distributed fuels.

However, the environment changes. There was a demand for greater levels of artificial regeneration, and an increasing demand for the use of prescribed fire for site preparation. Harvesting techniques have changed, with a trend away from conventional cut and skid operations to more mechanized systems, which have changed the distribution of cutover fuels, with large concentrations of slash at landings and roadsides and much less fuel in the cutover itself.

Canadian agencies tried to meet these challenges with the introduction of the helitorch. The torch generates more fire, faster, than the AID machine. It is better able to ignite large PBs, and to build and sustain fireline where fuels are patchy or discontinuous, or where there are significant inclusions of green material and wet areas, as frequently occur on highly productive mixed wood sites.

Conducting more burns, larger burns, and better burns, has demanded better planning tools. In the early 1980's, we began using remote weather stations to economically and reliably monitor weather conditions at PB sites beginning well in advance of the ignition date.

We also needed better information about fuel loadings and distribution. Most agencies in Canada use the fuel sampling system developed by the Canadian Forestry Service, now Forestry Canada, for measuring and calculating fuel loads (McRae et al. 1979). We now have an even more important planning tool, the Canadian Forest Fire Behaviour Prediction System, a component of the Canadian Forest Fire Danger Rating System, to aid in the prediction of burn behaviour and fuel consumption (Alexander et al. 1984). In Ontario, we use the Fire Behaviour Prediction System in conjunction with a detailed PB planning manual to produce a lengthy and well-documented burn plan.

These and other technologies, such as the site classification system used in British Columbia, have allowed Canadian fire management agencies to make significant progress in their prescribed burning programs during the past ten years.

However, new technologies are generally not cheap. Hardware items such as the helitorch have significant capital and maintenance costs. Electronic technologies such as remote automatic weather stations are likewise expensive to acquire, and require a more sophisticated level of maintenance than conventional manned stations. The research efforts needed to build a fire behaviour prediction system are expensive, and research resources are limited.

New technologies often have another downside, the hidden costs that we didn't anticipate, or didn't expect to be so significant. The law of unintended consequences comes into play, where you end up requiring a second technology to deal with the unexpected problems wrought through using the first technology.

The introduction of the helitorch is a good example. The torch has without question been a great asset to enhancing prescribed fire programs. But the use of the torch has the potential to create problems we didn't usually experience in the past. The torch gives us the ability to light a lot of fire in a hurry, particularly when using the centre-fire or convection burning technique.

We now have the potential to release a large amount of energy in a short period of time. We know that we need to be more aware of the rate of energy release, the stage of convection column development, and the interaction of the column with the atmosphere. In Ontario, we have recently generated some interesting fire behaviour including vigourous fire whirlwinds on prescribed burns using mass-fire ignition.

In response to this problem, we have begun a program of using portable minisondes to provide on-site upper air observations on large PBs. The minisonde data allows us to get a better picture of the vertical structure of the atmosphere above the fire, and to better predict the impact that may have on the behaviour of the fire.

These kinds of technological problems or challenges are not trivial, but they are of a nature that research and operational agencies are used to dealing with, have successfully addressed in recent years. However, there are other changes in our operating environment that are more difficult to deal with, particularly those brought about by political and social pressures.

For example, virtually all prescribed burning in Ontario is carried out by the provincial Ministry of Natural Resources. The fire management program provides prescribed fire as a service to the other resource managers. This is not the case in all provinces. In British Columbia for example, the forest industry conducts many of the burns on their own limits. In Quebec, the fire management program, including prescribed burning, is provided by non-profit conservation societies funded jointly by the government and the major landowners. In Ontario, although we are moving to get more industry involvement in the program, prescribed burning is still primarily a government operation.

For this reason, burning is subject to some of the unusual constraints placed on public sector operations; such as the fact that, to most governments, all budgetary dollars are not created equal. There are salary dollars which pay employee wages and overtime, and there are "other" dollars, which pay for everything else.

The problem is that prescribed burning is still a relatively labour intensive operation, at least the way we do it in Ontario. British Columbia does carry out burns where, because of terrain and burning conditions, they are able to ignite fires and monitor them with relatively few staff, but in our province this is not the case. It takes a lot of people to plan the burn and to sample fuels. We need an ignition crew, suppression staff, an overhead team, safety people, and so on. All of these people generally want to be paid, and we want to charge those salary costs back to the client.

Unfortunately, governments, in response to public concerns, valid or otherwise, about the size of the public service payroll, would prefer to supply programs not with salary dollars, but with "other" dollars. So we often face the situation where prescribed fire is the desired site preparation treatment for an area, but it is bypassed in favour of more expensive, and perhaps less effective mechanical treatment, because the "other" dollars that pay for mechanical work are available while the salary dollars needed for prescribed burning are not.

For some reason, the logic of this escapes me. Perhaps these funding anomalies are peculiar to our organization in Ontario. Nonetheless, we will have difficulty expanding the PB program, or even maintaining it at current levels as salary allocations continue to decline. There are some approaches to follow, and we are pursuing some of these now, including more involvement of the forest industry in burning programs on their own limits. We need the ability to market prescribed fire to our clients as a cost-effective regeneration technique, without being restricted by the colour of the money they need to pay for it. Political pressures and budget restraints are not limited to Ontario; I'm sure other agencies are subject to problems not unlike our current salary crunch.

The final aspect of changing environments I want to discuss is the increasing public and regulatory concern over our physical environment. Those of you from the western United States are no strangers to fairly stringent controls over the environmental impacts of prescribed burning, but the pressures are building in Canada as well. Difficulties with smoke production and air quality are perhaps more acute in the well-populated mountain and canyon terrain in the west, but the public and regulatory bodies are expressing concern in most other jurisdictions as well. In Ontario currently there are two regulatory thrusts that are likely to have an impact on the delivery of the prescribed burning program.

The entire process of timber management carried out by the Ontario Ministry of Natural Resources is subject to a class environmental assessment now proceeding under the auspices of the Ministry of the Environment. Prescribed burning will be receiving scrutiny as a site preparation technique. It is difficult to project the results of the environmental assessment process, but at a minimum we will be faced with some rather tough questioning about burning practices and long-term impacts.

The other regulatory activity now underway is also being carried out by the provincial Environment Ministry as they rewrite the regulations governing the control of air quality and sources of air pollution. They have already advised us that prescribed burning will be subject to a code of practice to ensure that our activities are in line with air quality and other environmental standards. We are not certain as yet what impact this code of practice will have, but we are working now with the Environment Ministry on preliminary discussions.

It seems quite possible that during the public hearings at the Environmental Assessment, or during the Code of Practice discussions, questions will be raised to which we don't have very good answers. Or, we may have answers without much quantitative data to back them up. Neither situation is very desirable when your program is being examined by the public or a regulatory agency.

Since 1987, the Ministry of Natural Resources in Ontario has been cooperating with Forestry Canada and the U.S. Forest Service in their joint study of the behaviour and impacts of large-scale prescribed fires. There are a number of papers at this conference related to this work and I will not describe it in any detail. We feel that this research will be critical to addressing many of the issues we expect to be raised about prescribed burning over the next couple of years. On a positive note, we recently succeeded in getting some research staff and atmospheric modellers with the Environment Ministry directly involved in this year's study plan. We have seen environmental regulation have a significant impact on prescribed burning programs in the western United States. I fully expect that significant changes may be coming in Canada as well. By sponsoring relevant research work, we hope to be able to meet public and regulatory demands about air quality and environmental protection, while still delivering an effective burning program.

I have tried to provide a Canadian perspective on these challenges, though I have to admit I have used my home province of Ontario as the case study in many instances. I think that our experiences here are indicative of the situation in the rest of the country. Although prescribed burning programs in Canada have progressed significantly in recent years, our changing environments demand that we continue to change and adapt our methods and approaches. Responsive management of prescribed burning programs and a continuing research and development effort will be required to maintain prescribed fire as a viable management tool through the next decade.

References

ALEXANDER, M.E., B.D. LAWSON, B.J. STOCKS AND C.E. VAN WAGNER. 1984. User guide to the Canadian Forest Fire Behaviour Prediction System. Interim edition. Dep. Environ., Can. For. Serv., Sault Ste. Marie, Ontario (unpublished report).

MCRAE, D.J., M.E. ALEXANDER AND B.J. STOCKS. 1979. Measurement and description of fuels and fire behaviour on prescribed burns: a handbook. Dep. Environ., Can. For. Serv., Info Rep. 0-X-287.

Fire Acceleration on Large-Scale Convection Burns

D.J. MCRAE AND B.J. STOCKS
Forestry Canada, Ontario Region
Great Lakes Forestry Centre
Sault Ste. Marie, Ontario

C. J. OGILVIE
Forestry Canada, Northwest Region
Northern Forestry Centre
Edmonton, Alberta

Abstract

Large-scale prescribed burns are now being conducted routinely in many areas of Canada, primarily by using helicopter ignition, with a limited understanding of the mass fire behavior that results from interactions between multiple ignition lines. Quantitative guidelines on the proper spacing and rate of application of ignition firelines are not presently available. As a result, erratic fire behavior characteristics, such as fire whirlwinds, occur frequently.

An investigation into the manner in which ignition firelines spread and interact with each other, especially in the junction zone where firelines meet, was initiated in Ontario in 1986. Visibility problems as a result of smoke made aerial observations of fire spread impossible initially. Subsequently, a helicopter, fixed-mounted, infrared camera, coupled with a digitizer-analyzer, with imagery recorded directly on video film, was used to document ignition patterns and interactive fire spread rates. This paper describes ignition line spread rates on three prescribed burns conducted in northern Ontario in 1987 and 1988. The effect of the junction zone on fire acceleration, as the fire approaches the preceding fireline, is discussed. Results are compared with headfire equilibrium spread rates that would be predicted in the same fuel complex with the Initial Spread Index (ISI) of the Canadian Forest Fire Weather Index (FWI) System.

Résumé

Des brûlages dirigés à grande échelle sont maintenant effectués régulièrement dans de nombreuses régions du Canada; ils sont principalement allumés par hélicoptère, bien que les connaissances sur le comportement en masse d'incendies interactifs déclenchés par des foyers multiples soient minimes. Nous ne disposons actuellement pas de directives quantitatives sur les avantages de certains dispositifs d'allumage et sur l'espacement adéquat et le dosage des foyers d'incendie. L'irrégularité du comportement du feu, notamment des tourbillons de feu, est le problème le plus évident associé à ce manque de directives sur l'allumage.

Une étude sur la façon dont les lignes de feu se propagent et interagissent, notamment à leurs points de jonction, a été entreprise en Ontario en 1986. Les problèmes liés à la réduction de la visibilité par la fumée empêchaient auparavant les observations aériennes de la propagation du feu. Une caméra infrarouge héliportée (qui rencontra les spécifications militaires) liée à un analyseur-convertisseur analogique numérique et dont l'imagerie était directement enregistrée sur bande vidéo a été utilisée pour enregistrer les tendances de l'allumage et les taux de propagation interactive du feu. Ce document décrit les taux de propagation en ligne de l'allumuge observés lors de trois brûlages dirigés effectués dans le nord de l'Ontario en 1987 et 1988. Les effets de la zone de jonction sur l'accélération du feu à mesure que celui-ci se rapproche de la ligne de feu précédente sont examinés. Ces résultats sont comparés aux vitesses de propagation d'équilibre d'un feu sous le vent qui pourraient être prédites dans un même complexe de combustibles à l'aide de l'indice de propagation initiale (IPI) de la Méthode canadienne de l'Indice Forêt-Météo (IFM).

Introduction

Large-scale prescribed burns are now routinely conducted in many areas of Canada, and have proven to be very cost-effective as a site preparation technique for both forest and wildlife management purposes. However, a trend toward large-scale, convection-style burns, usually ignited quickly by helitorch, has occasionally resulted in the generation of extremely intense fires and erratic fire behavior, caused by rapid ignition, long lines of ignition, and interactions among multiple ignition lines. Large fire whirlwinds up to 400 m in diameter are a prominent example of erratic fire behavior on Ontario prescribed burns, on which igni-

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

tion rates of 400-500 ha/hr are common (McRae and Stocks 1987). Fire managers require a much better understanding of interactive mass fire behavior in order to conduct large-scale prescribed fires in a safe, effective, and efficient manner. Ignition guidelines that describe the proper spacing and rate of application of ignition firelines are essential.

Canadian fire researchers have tried in the past to document fire spread rates by means of various techniques. Ground-based visual observation, with stopwatches to time fire spread over known distances (measured before or after the fire), has been the most common method. Problems associated with obscured visibility from smoke and with safety of personnel were common. Throwing numbered metal tags into the fire front at given intervals is another version of this technique that requires research personnel to work very close to the fire. Other methods have been developed so that close visual contact with the fire is not required. A physical measuring device was used in some Canadian studies (Stocks and Walker 1972, McRae 1985, Stocks 1987) in which wires were attached with string to metal stakes at known grid points within the study area; each wire was run to a sawhorse located outside the burn area, and weighted so that it would fall when the fire reached the stake and burned through the string. In recent years the use of buried electronic timers, developed by Blank and Simard (1983) and modified by McRae (1986), has provided a dependable and portable device for determining times of fire passage past known points. Most recently a "thermologger" has been developed, which can be buried and used to record flame-zone temperatures and residence times, in addition to fire spread rates.[1]

These rate-of-spread measuring devices, however, are useful only in small experimental fires on which fire ignition is usually by hand (point-source or line fire). An unrealistic number of these devices would be required to adequately document interactive fire behavior on large-scale, mass-ignition burns. Aerial observation, by using infrared technology, seemed most likely to provide the capability to monitor fire behavior on this type of large-scale fire.

In 1986 a Canada/United States cooperative mass fire behavior and atmospheric environmental impact study was initiated in which fire research scientists from both countries agreed to exchange personnel, equipment, and data in order to investigate large-scale mass fires. This international study, whose goal was to model the entire prescribed fire process, includes investigations of fire dynamics, convection column dynamics, and smoke chemistry on large-scale prescribed burns (Stocks 1989). Researchers from Forestry Canada (FORCAN) are participating in this study, with emphasis on the fire dynamics of mass-ignition prescribed burns. The present paper describes the interactive spread rates documented with airborne infrared equipment on three large prescribed burns conducted in northern Ontario in 1987 and 1988, with particular emphasis on fire acceleration and the importance of the junction zone as mass-ignited firelines join.

Methods

STUDY AREA DESCRIPTIONS

During the cooperative study, three operational burns (Hardiman Township, Battersby Township, and Peterlong Lake), planned and conducted by the Ontario Ministry of Natural Resources (OMNR) in compliance with their prescribed burning manual (Anon. 1987), have been monitored and documented. These burns were located in the Timmins-Chapleau-Gogama region of northern Ontario, an area located in the Missinaibi-Cabonga Section of the Boreal Forest Region (Rowe 1972). All three sites were harvested commercially: Battersby Twp (718 ha) was cut conventionally (tree-length) whereas Hardiman Twp (323 ha) and Peterlong Lake (217 ha) were harvested by the full-tree method. Jack pine (*Pinus banksiana* Lamb.) was the major species on each site, with various proportions of black spruce (*Picea Mariana* (Mill.) B.S.P.), trembling aspen (*Populus tremuloides* Michx.) and white birch (*Betula papyrifera* Marsh.) also present. All slash created was less than one year old when it was burned. Fuel loads (Table 1) for all sites were measured by the procedures of McRae et al. (1979). All ignition was done from the air with a helitorch.

Table 1. Preburn loads and fuel consumption data for the Hardiman, Peterlong, and Battersby burns.

	Slash fuel loads (kg/m^2)					
	0-6.9 cm size class		≥7.0 cm size class		Depth of Burn	Total fuel consumption
Prescribed burn	Preburn	Consumption	Preburn	Consumption	(cm)	(kg/m^2)
Hardiman	1.8	1.5	2.2	0.6	3.2	4.7
Battersby	2.3	1.9	3.3	1.0	2.9	5.1
Peterlong	2.1	1.3	4.1	1.5	2.3	4.3

FIRE SPREAD MEASUREMENTS

A helicopter, fixed-mounted, infrared camera (Barr and Stroud IR18), coupled to a digitizer-analyzer (Compuheat VIPS 300), with imagery continuously recorded directly onto VHS video tape, was used to record interactive fire behavior on each burn. The camera looks at the 8-13 µm spectral bandwidth; has a field of vision of 77° x 52° with a resolution of 1.73 mRad and has a minimal resolvable temperature (MRT) of 0.17-0.35°C. The use of a helicopter allowed the camera to remain stationary over the prescribed burn during ignition. Videotaping permitted the ignition and fire growth sequences to be analyzed later. A clock superimposed on the video image kept a continuous record of time. Both a normal and a wide-angle camera lens were used. The wide-angle lens is more suitable when an overall view of the prescribed burn is desired, whereas the normal lens is best when concentrating on fire spread in a particular portion of the overall burn. The wide-angle lens also permits operation of the helicopter at lower altitudes. On these burns the helicopter (Bell 206), operating with one rear door removed in order to mount the camera, flew at lower heights to allow better protection of the camera operator from the severe cold present at the higher altitudes. Depending on lens usage and fire coverage required, the helicopter was flown at an altitude of between 1800 and 3200 m above ground.

Postfire analysis of the tape with the digitizer-analyzer was carried out in order to determine ignition line spacing, fire spread distances, and acceleration rates. The digitizer-analyzer corrects the scales of the images from the altitude data and the field of view of the camera lens. The area of flaming and smoldering combustion can also be determined by density-slicing techniques with the digitizer-analyzer.

The procedure followed to determine acceleration between ignition lines was to identify a number of individual ignition points soon after an ignition line had been established, and to monitor the growth of the fire from that ignition point until it merged with the previous ignition line. At various times during this process the forward spread rate was calculated, with particular emphasis on determining the increasing acceleration in the junction zone area at which the convective influence of the established fire on the latest ignition line became apparent.

For each of the three prescribed fires in this study one portion of the area within the burn was selected for detailed, interactive fire-spread analysis. Care was taken to ensure that areas chosen were representative, in terms of both fuel characteristics and ignition technique, of the complete burn.

FIRE WEATHER DATA

A complete remote fire weather station was established on each prescribed burn site at least a month before the actual burn. Daily 1200 hr Local Standard Time observations of dry-bulb temperature, relative humidity, 10 m open wind speed, and precipitation were taken in order to calculate the fuel moisture codes and fire behavior indices (Table 2) of the Canadian Forest Fire Weather Index (FWI) System (Anon. 1984, Van Wagner 1987).

RESULTS AND DISCUSSION

The helicopter-mounted infrared equipment proved to be a very practical and valuable means of monitoring interactive fire behavior on large-scale, mass-ignited prescribed burns. While the helicopter hovered continuously the infrared camera provided high-resolution images that were later analyzed to determine actual fire spread rates. The only problem, of a minor nature, was the inability of the helicopter to remain absolutely stationary at all times. Generally, some forward motion is always required, which results in the helicopter moving away from the area of interest and having to reposition itself periodically. This usually means that the camera is not in the desired position for short periods. During the 1987 Hardiman Twp burn, the video monitors in the digitizer-analyzer package were located in the rear of the helicopter, which meant that the pilot was unable to see where the camera was looking. In 1988 a monitor was placed in the front of the helicopter to enable the pilot to view the burn area continuously and thus to maintain his position better.

The Hardiman, Battersby, and Peterlong prescribed burns were all conducted in mid-to-late August, with fire danger conditions under which the component fuel moisture codes of the FWI System barely reached the bottom of the desired prescription range (as reflected by the FWI System components). As a result, fuel consumption and fire intensity levels were somewhat low; however, the operational objectives of each burn, in terms of areal coverage and fuel reduction, were adequately met.

HARDIMAN TOWNSHIP PRESCRIBED BURN

This 323-ha prescribed burn was conducted on 27 August, 1987 under clear skies. Winds were very light during the burn, which resulted in an upright convection column that reached 4200 m in height, with a well developed capping cumulus cloud (Fig. 1). The burn was ignited in two blocks over a 3-hr period by means of a strip-headfire ignition technique. As the site has

Table 2. Fire weather and fire danger ratings for the Hardiman, Peterlong, and Battersby burn sites.

Prescribed burn	Date (d/m/yr)	Dry-bulb temperature (°C)	Relative humidity (%)	Wind speed (km/hr)[a]	Wind direction (degrees)	FWI System component[b]					
						FFMC	DMC	DC	ISI	BUI	FWI
Hardiman	28/08/87	18.0	44	5.0	225	88	15	257	4.0	26	8
Battersby	12/08/88	29.4	58	12.4	225	88	15	271	6.6	27	11
Peterlong	22/08/88	22.0	35	17.0	135	90	19	245	10.4	32	18

[a] 10-m open wind speed.

[b] Abbreviations are: FFMC-Fine Fuel Moisture Code, DMC-Duff Moisture Code, DC-Drought Code, ISI-Initial Spread Index, BUI-Buildup Index, and FWI-Fire Weather Index. Further component definitions of the FWI System may be found in Anon. (1984).

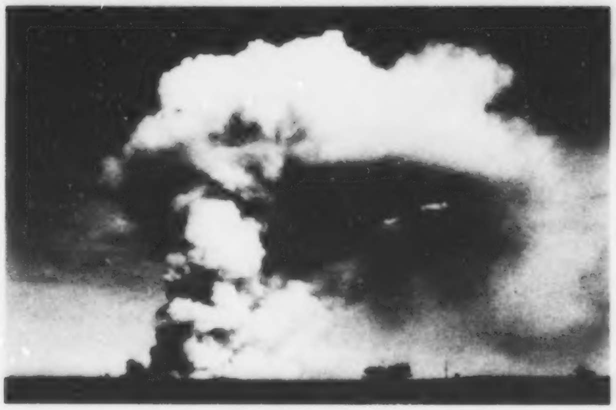


FIG 1. The Hardiman Township prescribed burn convection column, viewed from a distance of 12 km. This picture was taken approximately 2.5 hr after ignition began. At this point the column height was 4100 m.

been full-tree logged, fuels were somewhat discontinuous. The upright convection column on this prescribed burn created some difficulties, as the helicopter had to be positioned very close to the column in order to record the ignition sequence, and this resulted in some turbulence.

Maximum spread rates were measured for 30 separate ignition points on the Hardiman burn and are presented in Table 3, along with the distances covered while achieving these maximum spread-rate values. The portion of the prescribed burn in which these measurements were made is shown in Figure 2. The outline of the hot core of a fire whirlwind can also be seen in the left center of this picture (note arrow). This vortex traversed the burn area for 1 km, removing slash pieces and organic material in its path.

Earlier studies on non-convection style prescribed burns in jack pine slash in Ontario were conducted to determine the relationship between equilibrium (steady-state) headfire spread rates and the Initial Spread Index (ISI) component of the FWI System (Stocks and Walker 1972, Alexander et al. 1984). This relationship predicts equilibrium spread rates of approximately 6 m/min for an ISI of 4.0 as measured at the Hardiman site. From Table 3, it is evident that much higher spread rates (up to 61 m/min) were common on the Hardiman burn, particularly in junction zone areas. This is undoubtedly a result of a strong convective influence and the resultant interaction between ignition lines.

BATTERSBY TOWNSHIP PRESCRIBED BURN

The Battersby prescribed burn was carried out on 12 August 1988 under broken to locally overcast cloud conditions that resulted from an approaching storm system. Although relative humidity levels rose throughout the afternoon, deep convection was possible and a column that reached heights in excess of 6500 m was produced. This column was capped by a large cumulonimbus cloud that generated precipitation downwind from the burn. This 718-ha fire was ignited, by a combination of strip-headfire and center-fire ignition, over a 4-hr period.

Maximum spread rates were measured for 28 separate ignition points on a portion of the Battersby burn that was ignited as a center-fire, and these are presented in Table 3. Figure 3 shows the area within the burn in which these measurements were made, and also illustrates the presence of a number of barriers to fire spread, including uncut stands and logging roads. The

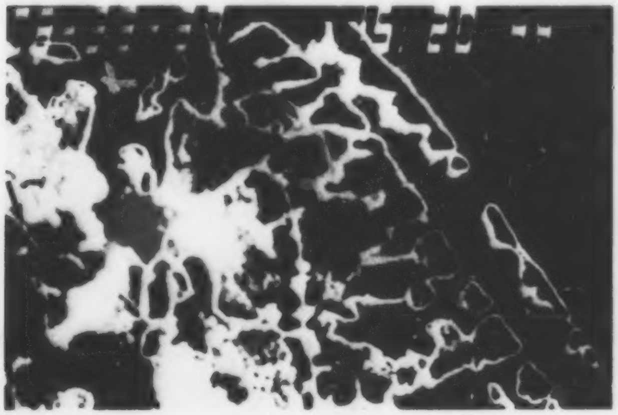


FIG 2. One frame of the infrared video tape, which shows a strip head-fire ignition sequence in progress on the Hardiman Township prescribed burn. Note the hot core outline of a fire whirlwind in the left, middle portion of the picture (see arrow).

FIG 3. The center-fired portion of the Battersby Township prescribed burn in which spread measurements were made. The dark areas within the ignited area are uncut stand and cutting roads. The helicopter skid appears in the picture, taken with a wide-angle lens.

Table 3. Maximum fire spread rates for different ignition points found on three recent Ontario prescribed burns.

Ignition point	Hardiman Township		Battersby Township		Peterlong Township	
	Maximum rate of spread (m/min)	Distance of run (m)[a]	Maximum rate of spread (m/min)	Distance of run (m)[a]	Maximum rate of spread (m/min)	Distance of run (m)[a]
1	61.6[b]	105.5	47.5[b]	71.6	42.9	47.2
2	52.4[b]	80.0	34.1[b]	83.5	40.2[b]	57.0
3	47.5[b]	61.0	31.7[b]	43.6	33.1[b]	50.6
4	46.9[b]	89.6	25.3[b]	36.9	30.3[b]	43.6
5	46.2[b]	87.5	21.9	45.7	30.2	59.1
6	43.3	65.5	21.4[b]	42.1	21.5	39.6
7	39.6[b]	56.4	19.5[b]	51.9	21.3	32.0
8	36.6[b]	71.3	15.8	35.1	19.5[b]	50.0
9	36.6[b]	89.3	14.8	39.6	16.7	34.7
10	36.6	55.2	14.6	32.3	15.0[b]	78.0
11	34.7[b]	35.1	14.6	42.1	13.7	36.6
12	34.1[b]	61.9	13.7	25.3	13.6	23.5
13	32.3	34.4	13.6[b]	38.4	12.6[b]	61.9
14	30.5	44.2	13.4[b]	53.3	6.1	51.9
15	28.0	53.6	13.4	21.0	-	-
16	25.8	60.4	13.4	23.5	-	-
17	24.4	53.0	13.4	49.1	-	-
18	24.0	43.9	12.9	40.2	-	-
19	23.8	93.9	12.4	29.3	-	-
20	23.8	74.7	12.2	22.3	-	-
21	22.3[b]	46.6	12.2	33.5	-	-
22	20.7	96.6	11.0	43.0	-	-
23	20.7	59.4	10.5	23.5	-	-
24	19.5	48.2	10.5[b]	30.5	-	-
25	19.5[b]	86.0	9.8	32.9	-	-
26	16.5	87.5	9.4	26.2	-	-
27	9.1	38.1	5.7	18.9	-	-
28	8.8	44.2	2.4	21.6	-	-
29	7.3	33.2	-	-	-	-
30	4.9[b]	32.9	-	-	-	-

[a] Distance from initial ignition point to the point at which maximum rate of spread was measured.

[b] These fire acceleration rates were recorded when the firefront was converging with the previous fireline (junction zone).

ISI value of 6.6 calculated at the Battersby site translated into projected steady-state headfire spread rates of 10-11 m/min and, although the fires at many of the monitored ignition points spread at approximately that rate, spread was more rapid at a number of points, particularly those in junction zones.

Figure 4 is a detailed schematic diagram of the center-fired portion of the Battersby burn in which interactive spread rates were measured, and is intended to illustrate some of the fuel continuity problems that affected spread rates. Table 4 contains a detailed record of spread rates for five individual ignition points (shown in Figure 4) and highlights the variation in these spread rates at various times as fires at these points expanded toward the main fire area. Spread of the fire at points A and B was impeded by uncut black spruce thickets, although fires at these points eventually joined with the main fire and exhibited greatly increased spread rates in the junction zone. Growth from point C was stopped by a road. Points D and E were located in areas of continuous slash fuels and spread at these points was unimpeded, which generally resulted in steady-state spread rates over much of their growth period and increased spread rates as acceleration took place in the junction zone areas.

PETERLONG LAKE PRESCRIBED BURN

This 217-ha prescribed burn was carried out on 22 August 1988 under clear skies. Surface winds were reasonably strong (17 km/hr) during the burn, with a strong upper-air inversion (2.7°C) existing at 2200-2400 m. The convection column was unable to penetrate this inversion, and leveled off at 2300 m without forming a capping cumulus cloud. Fuels were somewhat discontinuous over the site as the area had been full-tree harvested. A herbicide had been applied aerially in mid-June to reduce the abundance of green vegetation, but much of its effect had dissipated by the time the Peterlong fire was conducted. The burn was ignited in two blocks over a 2-hr period, by means of a combination strip-headfire and center-fire ignition pattern.

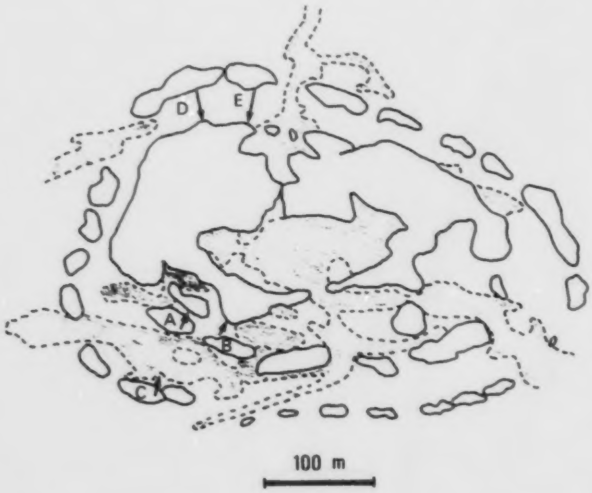


FIG 4. An outline of the Battersby Township fire at 14:38:48 LST, which shows the location of the ignition points (letters) described in Table 4. Shaded areas of the map indicate areas of poor slash continuity, ranging from black spruce stands to roads.

Table 4. Spread rates at selected ignition points for the Battersby Township prescribed burn.

Time period (LST)	Rate of spread (m/min) Ignition point[a] A	B	C	D	E
14:37:45-14:38:00	0.0	2.4	6.1	-	-
14:38:00-14:38:48	4.2	2.7	1.5	29.7	24.0
14:38:48-14:39:35	3.5	3.1	2.3	12.1	0.4
14:39:35-14:40:06	2.3	4.1	12.4	10.0	12.4
14:40:06-14:40:21	0.0	11.1	0.0	11.0	17.1
14:40:21-14:40:36	1.2	0.0	8.5	11.0	17.1
14:40:36-14:42:05	2.3	2.3	3.1	3.7	20.1
14:42:05-14:42:20	31.7	31.7	8.5	47.5	34.1

[a]The positions of the ignition points can be seen in Figure 4.

Maximum spread rates, measured for 14 separate ignition points on the Peterlong burn, are shown in Table 3. Equilibrium headfire spread rates, calculated from the ISI value of 10.4 measured at the Peterlong site, would be predicted to be approximately 16-18 m/min. Many of the interactive spread rates for the Peterlong burn are much higher. Once again, this is the result of the strong convective influence of preceding ignition lines.

Conclusions

Helicopter-mounted infrared technology proved to be a useful and promising means of monitoring and documenting interactive fire behavior on large-scale mass-ignition burns. Although some difficulties, primarily as a result of helicopter positioning and fuel discontinuities, were encountered on the three prescribed burns discussed in this paper, greatly increased spread rates were measured as ignition lines accelerated in junction zones. Over the next few years additional fires will be studied to determine more accurately the acceleration of ignition lines under the influence of convection. This will require documentation of fires in uniformly continuous fuels, such as rehabilitation burns on which standing trees have been tramped down by bulldozers, and interactive fire spread can occur unimpeded. This information will be essential in the development of ignition guidelines that contain information on line spacing and application rates, and will also be vital in modeling convection-column dynamics and smoke dispersal when an accurate estimate of ground-level energy release rates is required.

Acknowledgments

Funding to rent and operate the infrared system used in this study was provided by the OMNR Aviation And Fire Management Centre and the Canada-Ontario Forest Resource Development Agreement (COFRDA), and is gratefully acknowledged by the authors. The continued cooperation and logistical support of OMNR (Aviation And Fire Management Centre, Northern Region, Gogama District and Timmins District) is also greatly appreciated.

Endnotes

[1] Thermologgers were developed by the Pacific Forestry Centre (Forestry Canada) in cooperation with Forest Technology Systems Inc., Victoria, B.C.

References

ALEXANDER, M.E., B.D. LAWSON, B.J. STOCKS AND C.E. VAN WAGNER. 1984. User guide to the Canadian Forest Fire Behavior Prediction System: rate of spread relationships. Interim edition. Dep. Environ., Can. For. Serv., Sault Ste. Marie, Ont. (unpublished report).

ANONYMOUS 1984. Tables for the Canadian Forest Fire Weather Index System. 4th ed. Dep. Environ., Can. For. Serv., Ottawa, Ont. For. Tech. Rep. No. 25.

ANONYMOUS 1987. Prescribed burn planning manual. Ont. Min. Nat. Resour., Aviation and Fire Manage. Centre, Sault Ste. Marie, Ont.

BLANK, R.W. AND A.J. SIMARD. 1983. An electronic timer for measuring spread rates of wildland fires. USDA For. Serv. Res. Note NC-304.

MCRAE, D.J. 1985. Prescribed burning of boreal mixed wood slash in the Ontario Clay Belt Region. Gov't of Can., Can. For. Serv. Inf. Rep. 0-X-367.

MCRAE, D.J. 1986. Prescribed burning for stand conversion in budworm-killed balsam fir: an Ontario case history. For. Chron. 62: 96-100.

MCRAE, D.J. AND B.J. STOCKS. 1987. Large-scale convection burning in Ontario. p. 23-30 In Proc. Ninth Conference on Fire and Forest Meteorology, 21-24 April 1987, San Diego, CA. Amer. Meteorol. Soc., Boston, Mass.

MCRAE, D.J., B.J. STOCKS AND M.E. ALEXANDER. 1979. Measurement and description of fuels and fire behavior on prescribed burns: a handbook. Dep. Environ., Can. For. Serv., Sault Ste. Marie, Ont. Inf. Rep. 0-X-187.

ROWE, J.S. 1972. Forest regions of Canada. Can. For. Serv. Pub. No. 1300.

STOCKS, B.J. 1987. Fire behavior in immature jack pine. Can. J. For. Res. 17: 80-86.

STOCKS, B.J. 1989. The Canada/U.S. cooperative mass fire behavior and environmental impact study. In Proc. 1988 annual Meeting Northwest Fire Council "Fire Management in a Climate of Change", 14-15 Nov. 1988 Victoria, B.C. (in press).

STOCKS, B.J. AND J.D. WALKER. 1972. Fire behavior and fuel consumption in jack pine slash in Ontario. Dep. Environ., Can. For. Serv., Sault Ste. Marie, Ont. Inf. Rep. 0-X-187.

VAN WAGNER, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index. Gov't of Can., Can. For. Serv., Ottawa, Ont. For. Tech. Rep. 35.

Cambium Mortality Resulting From Broadcast Burning in Mixed Conifer Shelterwoods

K.C. RYAN
Intermountain Research Station, Forest Service
U.S. Department of Agriculture
Missoula, Montana

B.M. STEELE
Private Statistical Consultant
Missoula, Montana

Abstract

Three supplemental protection methods for reducing cambium mortality resulting from prescribed burning of leave trees (n = 518) were evaluated in two shelterwood harvested areas. Treatments included: burned without supplemental protection, application of a commercial fire retardant to fuels around the base of the tree prior to burning, similar application of detergent foam, and manual removal of fuels. Species tested were: Douglas-fir, western larch, western hemlock, western red cedar, western white pine, Engelmann spruce, and grand fir. Several prefire and postfire fuel and tree morphology covariates were also observed. Fuel mass was measured on transects placed in downhill, uphill, and both sidehill positions. Cambium condition (live vs. dead) was determined at ground-line in each of the four positions. Logistic discriminant analysis (LDA) was used to select potentially useful explanatory variables. The Newton-Raphson method was used to estimate coefficients in a logistic regression analysis of deviance to evaluate important variables influence on cambium survival in a multivariate model. Models were generated to predict cambium survival from variables that can be determined before burning and from variables requiring both before and after burning observations.

The LDA indicated that bark thickness squared was the best prefire tree morphology variable for predicting cambium survival. The mass per unit area of logs greater than 7.62 cm diameter was the best prefire fuel variable. A qualitative descriptor of the depth of bark char was the best postfire predictor of cambium survival. Analysis of deviance indicated cambium survival varied with treatment (retardant > foam > manual removal = no protection). Species also strongly affected cambium survival. In the prefire model species, differences in cambium survival were western larch > Douglas-fir > grand fir > western hemlock > western white pine > Engelmann spruce = western red cedar. The same pattern occurred in the postfire model except that western white pine was not significantly different from Engelmann spruce. Diameter and either quantitative or qualitative prefire fuel descriptors also improved fit. Species and a qualitative descriptor of bark charring were the strongest postfire variables for predicting cambium condition.

Résumé

Une étude a été effectuée pour évaluer l'efficacité de trois méthodes de protection supplémentaire destinées à réduire la mortalité du cambium provoquée par un brûlage dinigé d'arbres à feuilles caduques (n=518) dans des secteurs exploités par coupes progressives. Les traitements comprenaient le brûlage sans protection supplémentaire, l'application d'un retardant commercial ou d'un écume de détergent aux combustibles entourant la base des arbres et l'élimination à la main des combustibles. Les essences comprenaient notamnent le Douglas taxifolié, le mélèze occidental, la pruche occidentale, le thuya géant, le pin argenté, l'épinette d'Engelmann et le sapin grandissime. Plusieurs covariables de la morphologie de l'arbre et du combustible pré- et post-incendie ont également été observées. La biomasse de combustible a été mesurée dans des transects établis vers le bas et vers le haut de versants ou en position latérale (deux côtés). L'état du cambium (vivant ou mort) a été déterminé au niveau du collet dans chacune des quatre positions susmentionnées. Nous avons eu recours à l'analyse discriminante logistique (ADL) pour choisir les variables explicatives pouvant s'avérer utiles. Nous avons utilisé la méthode Newton-Raph-son pour estimer les coefficients dans une régression logistique de vraisemblance maximale pour effectuer une analyse de déviance pour évaluer influence de chaque variable importante sur vulnérabilité du cambium dans un modèle multivariable.

Des modèles ont été gérérés pour prédire la survie du cambium à partir de variables qui peuvent être déterminées avant le brûlage et à partir de variables qui nécessitent que des observations soient prisent avant et après le brûlage.

L'ADL a indiquée que l'épaisseur de l'écorce au carré était la meilleure variable morphologique de l'arbre pré-incendie pour prédire l'étát du combium. La meilleure variable pré-incendie du combustible était la superficie de la masse par unité des tronco d'arbres ayant un diamètre plus élevé que 7,62 cm. La prédiction, post-incendie de l'était du cambium la plus fiable etait un descripteur qualitatif de l'épaisseur de la carbonisation de l'écorce.

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

L'analyse de la déviance indiquait que l'état du cambium variait avec le traitement (retardant > écume > élimination à la main = aucune protection). Les espèces ont aussi fortement affectée l'état du cambium. Les différences dans la vulnérabilité du cambium dans les espèces du modèle pré-incendie étaient le mélèze occidental > Douglas taxifolié > sapin grandiosime > pruche occidentale > pin blanc occidentale > épinette d'Englemann = cèdre rouge occidentale. Les mêmes résultats se sont produits dans le modèle post-incendie sauf que le pin-blanc occidental n'était pas significativement différent de l'épinette d'Engelmann.

Le diamètre et des descripteurs quantitatifs et qualitatifs du combustible pré-incendie ont également permis d'améliorer de façon significative l'ajustement. L'essence et un descripteur qualitatif de la carbonisation de l'écorce étaient les variables post-incendie les plus fiables pour prédire l'état du cambium.

Introduction

Each year shelterwood and seed-tree regeneration methods are applied on hundreds of hectares in mixed conifer stands in grand fir, cedar, and hemlock habitat types of the Northern Rocky Mountains. Of these, many hectares are on steep sites where mechanical equipment cannot be used for fuel treatment and site preparation. Hand piling large areas of logging slash is prohibitively expensive and does not ensure adequate site preparation. Trees in these stands exhibit a wide range of resistance to fire, and broadcast burning often results in unacceptably high mortality. Because treatment of logging slash and forest floors is needed for hazard reduction and site preparation, respectively, methods are needed to predict fuel conditions that lead to fire-caused injury.

Presently, little information exists concerning the use of fire for hazard reduction and site preparation in partial cut stands containing a mix of fire resistant to nonresistant trees without excessive mortality. The potential benefits of partial cutting, particularly shelter and a local seed source, are lost by excessive mortality. Ryan and Reinhardt (1988) developed logistic regression models for predicting mortality of several species common to these habitat types following slash burning. They also developed guidelines for slash burning in these stands (Reinhardt and Ryan 1988). Their work illustrates the importance of bark thickness in resisting cambium injury during burning. It also clearly indicates that some species and diameters cannot be successfully burned in standard operational prescribed fires. Additional treatments are needed if prescribed burning is to be used for hazard reduction and site preparation in these types. The objectives of this study are to determine fuel conditions associated with cambium injury to different species and diameters of leave-trees in partial cut stands, and to evaluate the effectiveness of three supplemental protection methods for reducing fire-caused injury. This paper reports preliminary results of the study.

Methods

STUDY DESCRIPTION

Two adjacent shelterwood harvested areas were burned on the Priest River Experimental Forest (PREF), Idaho Panhandle National Forests in northern Idaho (lat. 48° 21' N, long. 116° 45' W). One area was approximately 5 ha, had 205 trees, and was burned on September 22, 1983 (area 1). The other area was approximately 7 ha, had 313 trees, and was burned on June 26, 1984 (area 2).

Seven species were included: WL - western larch (*Larix occidentalis* Nutt.), DF - Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), GF - grand fir (*Abies grandis* [Dougl.] Lindl.), WH - western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), WP - western white pine (*Pinus monticola* Dougl.), WRC - western red cedar (*Thuja plicata* Donn), and ES - Engelmann spruce (*Picea engelmanni* Parry). Based primarily on bark thickness, the first two species have high fire resistance when mature but may be injured when immature or when heat from slash fires is excessive. The latter three species are susceptible to injury in virtually all slash fires regardless of age (Peterson and Ryan 1986, Ryan 1982).

Within each plot and species, trees were randomly assigned to one of the following treatments: (1) burned without supplemental protection; (2) application of mono-ammonium phosphate (Phos-Check G)[1] fire retardant to fuels within 3.6 m of the bole, (3) application of foam (Dawn liquid detergent and water applied through a Western Fire Equipment air aspirated nozzle) to the entire circumference on the lower 3 m of the bole and to fuels within 1 m of the bole, and (4) removal of all woody fuels larger than 2.5 cm diameter from within 1 m and scattering large concentrations within 3.6 m of the bole. In this latter treatment, no attempt was made to remove fuels smaller than 2.5 cm diameter but most of these were attached to larger branches so they were also removed.

Several prefire and postfire covariates were observed. In addition to species and treatment, diameter at breast height (DBH) was measured. Bark thickness squared was computed from species and DBH using published equations (Ryan 1982). The height to base of the live crown was also measured. Each tree was assigned an ocularly determined adjective rating of low, moderate, or high vigor.

Standard fuel inventory procedures (Brown 1974) were used to measure fuel mass before and after burning at each tree. Fuels were inventoried on four 0.91 m transects that radiated from the downhill, uphill, and both sidehill positions. Although much longer transects are normally neeeded to adequately sample large diameter fuels (>7.62 cm), more distant fuels are not thought to have a large effect on cambium condition near the base of the tree (cf. Ryan 1982). To conserve inventory time, 1-hour time-lag fuels (0.00 to 0.64 cm diameter) were not measured, and 10-hour time-lag fuels (0.64 to 2.54 cm diameter) were estimated on all four transects but measured only on one randomly selected transect per tree. Loadings (mass per unit area) of 100-hour time-lag (2.54 to 7.62 cm diameter), 1,000-hour time-lag (sound logs larger than 7.62 cm diameter), and rotten logs greater than 7.62 cm diameter were measured on all transects. In addition to loading, the total number of sound and rotten logs was also tallied. Fuel bed depth was measured at 0.30 m and 0.91 m from the tree. Duff depth was measured at 0.3 and 0.61 m. Changes in fuel loadings by size class, number of pieces greater than 7.62 cm, fuel depth, and duff depth were computed from inventory data. One of five ordinal ratings of fuel loading (i.e., very light = 1 to very heavy = 5) was ocularly estimated for each transect before and after burning and a rating change computed. The depth of bark char was classified into ordinal ratings (none, superficial, moderate, moderate-obviously dead cambium, deep, and deep-obviously dead cambium) (Ryan 1983). The moderate-obviously dead class was poorly represented (ca. 1% of observations) and not subjected to analysis. The depth of ground char (DGC) was assigned ordinal ratings (unburned, light, moderate, and deep) (Ryan 1983). Within 2 weeks after burning, vital staining (Ryan 1983) was used to determine cambium condition (live vs. dead) at ground-line in each of the four positions. Burning conditions are found in Table 1. Descriptive statistics for tree and fuel variables are in Tables 2 and 3, respectively.

ANALYSIS

Logistic discriminant analysis (LDA) was used to determine the predictive, or explanatory, potential of all available covariates. LDA uses logistic regression to estimate a discriminant function (LDF) for classifying a future observation of cambial condition on the basis of individual predictor variables (cf. Byth and McLachlan 1980, Crawley 1979, Press and Wilson 1978). A future observation upon cambial response is predicted to be survival if the predicted probability of survival is greater than 0.5, and predicted to be death if the predicted probability of survival is less than 0.5. The naive classification accuracy rate and the LDF classification rate were also computed.

This analysis provides two statistics of interest: the p-value for the test of significance of the predictor variable, and the apparent classification accuracy rate. The test statistic for the hypothesis (H_o: B = O) of the covariate as a predictor of cambial survival is the usual likelihood ratio. It was carried out by fitting two models: the model with the intercept and the covariate, and the model with the intercept as its only term. The difference in deviances between the two models is the likelihood ratio statistic. It is asymptotically chi-square in distribution, with degrees of freedom equal to the difference in the number of parameters between the two models. The likelihood ratio test is capable of detecting even slight associations between cambial mortality and the covariate when the sample size is large, as in our case.

The apparent classification accuracy rate is the fraction of correct classifications by the logistic discriminant function. This rate is compared to the naive classification accuracy rate, which is the accuracy rate if no information is known except the estimated probability of survival for the entire population. The apparent classification accuracy rate requires a strong association between the response variable and the classification variable for there to be much difference in the naive classification accuracy rate and the classification algorithm accuracy rate. Comparison of the classification algorithm accuracy rate to the naive classification rate suggests which variables are potentially major determinants of cambial mortality.

The analysis was carried out by drawing a 50% random sample from the entire dataset and regressing cambial response on each of the covariates except for bark thickness squared where the full sample was used. Discrete variables were treated by regressing cambial response upon indicator variables. LDA results were used to suggest candidate variables for multivariate logistic regression models for predicting the probability of cambium survival.

The Newton-Raphson method (McCullagh and Nelder 1983) was used to estimate the coefficients of the logistic regression model in an analysis of deviance. The approach is analogous to analysis of variance in ordinary least squares. Models were fit based on observation of two kinds of tree morphology and fuel variables: ones that are available prior to burning (prefire) and ones that require observations both before and after the fire (postfire). Fuel moistures and consumption were similar in the two fires, and preliminary analysis indicated cambium survival was also similar; consequently the effect of season was not significant. Thus, analysis did not differentiate between the two areas. Preliminary analysis indicated a high correlation between the estimated and actual 0.64 to 2.54 cm diameter fuels ($r = 0.94$) so estimated values were used in modeling cambium injury when actual values were not available. Uphill and downhill crown scorch heights were moderately correlated ($r = 0.80$), so analysis was restricted to uphill scorch. Preliminary analysis indicated cambium survival was similar between the deep and deep-obviously dead bark char classes, so these were combined.

The deviance statistic (the log-likelihood of the data multiplied by -2) was used to test statistical significance of factors and explanatory variables as a predictor of cambial condition. The statistic for this hypothesis test was the likelihood ratio statistic that is computed as the difference in deviances between a model that includes the explanatory variable and a model without the explanatory variable. Factors were represented in regression models by a set of indicator variables. A generalized Wald statistic (see Bishop et al. 1975, pp 348-353) and its associated p-value were used to test for significant differences between parameter estimates within factors.

Preliminary prefire and postfire cambial mortality models were used to generate local mean deviance (LMD) plots, a procedure analogous to the lack-of-fit test in ordinary least squares regression (Landwehr et al. 1984) for subsequent model testing. LMD plots were used to graphically compare inherent variation of the response variable to variation about the model (global mean deviance) as an informal test of the overall goodness of fit. Discussion of these techniques is beyond the scope of this paper, and interested readers are referred to Landwehr et al. (1984) for a discussion of why this approach is preferable to other statistics for evaluating goodness of fit. Residual plots were used to detect if there were specific observations for which the model predictions were substantially in error.

Results and Discussion

On average, trees were scorched on 65% of their circumference (Table 2). They were scorched to an average of nearly 6 m on the uphill side and to 1 m on the downhill. The depth of bark char was least on the downhill side and greatest on the uphill side of the tree. The probability of cambium survival showed patterns consistent with bark scorching. Cambium survival was 73% on the sides of the trees, 5% higher on the downhill side, and 7% lower on the uphill side.

The average fuel consumption on all transects was 61, 53, and 30% for the 10-, 100-, and 1,000-hour fuel size classes, respectively (Table 3). Fuel depths were reduced 58% while duff depths were reduced approximately 36%. The average fuel load rating was slightly above the moderate level. When compared to the percentages of fuel consumption there was little reduction in the rating as a result of burning. This indicates the ratings are not highly sensitive and are, possibly, biased toward the larger diameter fuels that experienced the least consumption.

LOGISTIC DISCRIMINANT ANALYSIS

Of the 11 tree morphology variables, including species, 9 had p-values indicating importance as predictors of cambium survival (Table 4). However, only species, bark thickness squared, crown base height, and depth of bark char produced improved LDF classification accuracy rates relative to the naive rates. Of the prefire tree variables, bark thickness squared provided the largest improvement in LDF classification accuracy over the naive estimate, while depth of bark char provided the largest improvement among the postfire variables. While there was a significant effect due to treatment, there was no improvement in the accuracy rate apparently because knowledge of other factors is needed to improve accuracy.

The height of crown scorch on the uphill side of the tree, the percentage of bole circumference scorched, and the heights of uphill and downhill bole scorch can logically be expected to be related to fireline intensity. While the likelihood ratio indicates that all but the last of these are significant, it is interesting that none of them improved the classification rate. One possible interpretation is that, across a wide range of fire resistances, fireline intensity is not strongly related to cambium survival near the ground line. This is further supported by the fact that our preliminary analysis did not find a significant difference between the two burns despite the fact that the fireline intensity in area 2 was an order of magnitude higher than in area 1 (Table 1).

Table 1. Burning conditions associated with fire treatments at Priest River Experimental Forest.

Condition	Area 1	Area 2
Temperature (C)	21	23
Humidity (%)	43	34
Wind ($m\ s^{-1}$)	2.3	2.5
1-hr m.c. (%)[1]	12	10
1,000-hr m.c. (%)[1]	24	34
Average duff m.c. (%)	83	100
Fireline intensity ($kW\ m^{-2}$)[2]	407	4,733

[1] 1-hr m.c. and 1,000-hr m.c. are the measured 0 to 0.64 cm diameter and > 7.62 cm diameter woody fuel moisture contents, respectively.

[2] Fireline intensity calculated from flame lengths observed according to methods in Ryan (1981).

Of the 20 fuel variables, 12 were significantly related to cambium survival but only 6 showed minor improvement over the naive rates (Table 5). The covariates yielding the greatest improvement in accuracy rates were measures of fuel consumption. The best postfire variable for predicting cambium condition was the change in the number of 1,000-hour logs (Table 5). It was followed closely by the change in the fuel load rating and the change in the loading of 100-hour timelag (2.54 cm to 7.6 cm diameter) woody fuels. These are suggestive of the importance of woody fuel consumption and the resultant energy release near the base of the tree in determining cambium condition.

Of the nine prefire fuel variables the 1,000-hour log loading provided the greatest improvement. The 0.91 m transect is at least an order of magnitude shorter than is normally used in inventory of large fuels (Brown 1974), and pieces frequently migrate in or out of transects during burning. As a result 1,000-hour loadings are highly variable (Table 3). It is somewhat suprising that the large log loading should be such a strong univariate predictor of cambium survival given this variability. The prefire depth of fuel at 0.30 m was highly significant and the LDF had an improved accuracy rate. This contrasts to the fuel depth at 0.91 m, which was not significant and provided no improvement over the naive classification rate. This suggests that in most cases fuel must be close to the bole to significantly influence cambium injury near the ground line.

Table 2. Sample size (n), mean, and standard deviation (s.d.) for tree related variables.

Variable	n	mean	s.d.
DBH (cm)	518	42.04	11.04
Squared bark th. (cm^2)	497	5.023	3.602
Crown base ht. (m)	508	16.79	5.442
Uphill crown sch. Ht. (m)	513	13.74	12.47
Downhill crown sch. ht (m)	511	10.19	11.41
Crown scorch (%)	513	23.44	32.70
Basal circum. sch (%)	516	65.40	40.36
Uphill bole sch. ht. (m)	511	5.852	5.517
Downhill bole sch. ht. (m)	507	1.047	1.609
Depth of bark char$_1$ [1]	518	2.606	1.632
Cambium condition$_1$	515	0.7806	0.4143
Depth of ground char$_1$	515	1.870	0.7171
Depth of bark char$_2$	517	2.950	1.589
Cambium condition$_2$	511	0.7260	0.4464
Depth of ground char$_2$	512	1.945	0.6774
Depth of bark char$_3$	516	3.279	1.713
Cambium condition$_3$	511	0.6595	0.4743
Depth of ground char$_3$	512	1.949	0.6660
Depth of bark char$_4$	515	2.959	1.664
Cambium condition$_4$	512	0.7363	0.4411
Depth of ground char$_4$	507	1.882	0.6547
Prefire vigor	517	2.219	0.7020

[1] Subscripts refer to position around the tree: (1- downhill, 2- right side, 3- uphill, and 4- left side).

Table 3. Sample size (n), mean, and standard deviation (s.d) for fuel related variables.

Variable	n	mean	s.d.
Measured 10-hour load (kg m^{-2})	519	1.090	0.9902
Estimated 10-hour load (kg m^{-2})	2072	1.007	1.032
Consumed 10-hour load (kg m^{-2})	2062	0.6175	1.076
Measured 100-hour load (kg m^{-2})	2072	1.860	2.185
Consumed 100-hour load (kg m^{-2})	2060	0.9568	2.100
Measured 1,000-hour load(kg m^{-2})	2072	9.240	23.87
Consumed 1,000-hour load (kg m^{-2})	2072	2.742	19.33
Number 1,000-hour pieces changed	2072	0.0656	0.7151
Rotten log load (kg m^{-2})	2072	1.612	9.308
Rotten log consumed (kg m^{-2})	2072	0.3651	9.029
Number of rotten logs	2072	0.0347	0.3372
Fuel depth 0.3 m (cm)	2072	25.79	31.24
Fuel depth 0.3 m change (cm)	2063	15.04	30.44
Fuel depth 0.91 m (cm)	2071	28.40	31.61
Fuel depth 0.91 m change (cm)	2060	16.42	30.87
Duff depth 0.3 m (cm)	1905	11.07	7.250
Duff depth 0.3 m change (cm)	1971	3.835	7.370
Duff depth 0.61 m (cm)	1904	10.45	7.143
Duff depth 0.61 m change (cm)	1971	3.942	7.130
Fuel load rating	2071	2.240	1.073
Fuel load rating change	2072	0.3687	1.240

Table 4. Logistic discriminant analysis likelihood ratios (LR), logistic discriminant classification function (LDF), and the naive classification rate for tree morphology variables. Each discriminant function was computed on the basis of a 50% random sample of the dataset except for bark thickness squared.

Variable	Likelihood ratio test			Apparent Classification Accuracy Rate		
	df	LR	p-value	LDF	naive	n
Treatment	3	33.0849	0.0000	0.7123	0.7123	994
Species	6	258.8807	0.0000	0.7472	0.7227	981
DBH (cm)	1	30.8055	0.0000	0.7201	0.7201	961
Squared bark th. (cm^2)	1	356.1069	0.0000	0.7573	0.7140	1965
Crown base ht. (m)	1	116.1623	0.0000	0.7575	0.7201	961
Uphill crown sch. ht. (m)	1	20.8354	0.0000	0.7236	0.7236	966
Basal circum. sch. (%)	1	111.5336	0.0000	0.7338	0.7338	988
Uphill bole sch. ht. (m)	1	12.4232	0.0004	0.7338	0.7338	988
Downhill bole sch. ht. (m)	1	0.0040	0.9493	0.7338	0.7338	988
Depth of bark char	3	378.4216	0.0000	0.8204	0.7185	991
Depth of ground char	2	171.5511	0.0000	0.7185	0.7185	991
Prefire vigor	2	3.4520	0.1780	0.7185	0.7185	991

Table 5. Logistic discriminant analysis likelihood ratios (LR), logistic discriminant classification function (LDF), and the naive classification rate for fuel variables. Each discriminant function was computed on the basis of a 50% random sample of the dataset.

Variable	Likelihood ratio test			Apparent Classification Accuracy Rate		
	df	LR	p-value	LDF	naive	n
10-hr load (kg m^{-2})	1	6.9502	0.0084	0.7331	0.7321	993
10-hr consumed (kg m-2)	1	39.0186	0.0000	0.7281	0.7321	993
100-hr load (kg m^{-2})	1	4.3583	0.0368	0.7321	0.7321	993
100-hr consumed (kg m^{-2})	1	18.6257	0.0000	0.7341	0.7321	993
1,000-hr load (kg m^{-2})	1	23.9580	0.0000	0.7335	0.7285	1002
1,000-hr consumed (kg m^{-2})	1	22.7692	0.0000	0.7355	0.7285	1002
No. 1,000-hr pieces changed	1	26.0507	0.0000	0.7365	0.7285	1002
Rotten log load (kg m^{-2})	1	1.1780	0.2778	0.7275	0.7285	1002
Rotten consumed (kg m^{-2})	1	0.8019	0.3705	0.7163	0.7154	1040
No. rotten pieces changed	1	2.1229	0.1451	0.7154	0.7154	1040
0.30 m fuel depth (cm)	1	22.8246	0.0000	0.7106	0.7154	1040
0.30 m fuel depth change (cm)	1	30.5390	0.0000	0.7135	0.7154	1040
0.91 m fuel depth (cm)	1	1.6128	0.2041	0.7421	0.7421	919
0.91 m fuel depth change (cm)	1	11.3127	0.0008	0.7388	0.7421	919
0.30 m duff depth (cm)	1	0.0140	0.9057	0.7421	0.7421	919
0.30 m duff depth change (cm)	1	1.5960	0.2065	0.7219	0.7219	960
0.61 m duff depth (cm)	1	0.7681	0.3808	0.7483	0.7483	886
0.61 m duff depth change (cm)	1	4.1546	0.0415	0.7530	0.7530	927
Fuel load rating	1	10.7431	0.0010	0.7530	0.7530	927
Fuel load rating change	1	19.6715	0.0000	0.7551	0.7530	927

Table 6. Analysis of deviance table for the prefire model.

Model	Deviance	d.f.	LR[1]	d.f.	p-value
A: intercept	2352.24	1964			
B: A + species	1839.62	1959	512.62	5	0.0000
C: B + treatment	1770.84	1956	68.78	3	0.0000
D: C + fuels	1682.43	1954	88.41	2	0.0000
E: D + DBH	1670.39	1953	12.04	1	0.0005

--Parameter estimates for model E--

Parameter	coeff.	std. error	Wald stat.	p-value
Intercept	-0.6363	0.2768	-2.2986	0.0215
Species				
Douglas-fir	2.9151	0.2549	11.4355	0.0000
Western white pine	0.6017	0.2034	2.9587	0.0031
Western hemlock	1.0193	0.2037	5.0047	0.0000
Western larch	3.7665	0.2607	14.4483	0.0000
Grand fir	1.4347	0.4016	3.5728	0.0004
Engelmann spruce	0.0000	-	-	-
Western red cedar	0.0000	-	-	-
Treatment				
Unprotected	-0.9762	0.1687	-5.7878	0.0000
Fuel removal	-0.7053	0.1876	-3.7597	0.0002
Retardant	0.4312	0.1937	2.2265	0.0260
Foam	0.0000	-	-	-
100-hr. load (kg m^{-2})	-0.1504	0.0308	-4.8650	0.0000
1,000-hr. load (kg m^{-2})	-0.0188	0.0031	-6.3990	0.0000
DBH (cm)	0.0194	0.0056	3.4480	0.0006

[1] LR - Likelihood ratio statistic

ANALYSIS OF DEVIANCE

Table 6 contains results for the analysis of deviance based on tree and fuel variables that are available prior to burning. The five models (A through E) include only variables that were found to significantly affect cambium survival. The likelihood ratio statistics clearly indicate that species, treatment, DBH, and both 100-hour and 1,000-hour fuels are significant predictors of cambium survival. There was not a significant difference between cambium survival of Engelmann spruce and western red cedar. Hence, these species are aliased and their coefficients are zero. Cambium survival of the remaining species was significantly greater. Among treatments the foam treatment is aliased, so its coefficient is zero. The retardant and foam treatments significantly increased survival, while survival was lower for the fuel removal and unprotected treatments. Additional pairwise comparisons indicated that, over the full range of fuels, species, and diameter, fuel removal was not significantly better than the unprotected treatment. Field observations indicated that 1 m clearing was not adequate unless fuels beyond the 1.0 m removal distance were light or trees were thick barked as in the case of Douglas-fir or western larch. Regardless of the statistical significance, the probability of cambium survival differed, on average, by only 6% between the most effective and least effective treatments. More complex models, not reported here, indicate significant interactions between species and fuels that are deserving of further investigation. As would be expected, cambium survival increased with DBH and decreased with greater woody fuel loadings.

Although LDA indicated that bark thickness squared provided the strongest prefire tree morphology univariate model for predicting cambium condition, squared bark thickness was not significant when included with treatment, fuel loading, DBH, and species. We conducted additional analysis that substantiated this result. Theoretical considerations (cf. Peterson and Ryan 1986) suggest cambium survival should be strongly related to bark thickness squared. Bark thickness increases linearly with diameter (cf. Ryan and Reinhardt 1988). The range of diameters and, therefore, bark thickness is relatively small for the various species. However, the effect of species and diameter on the cambium survival of these data cannot be ascribed solely to bark thickness. Clearly, additional research is needed to determine how resistance to cambium injury varies with species and size.

Table 7 contains results of the analysis of deviance for the models based on postfire variables. Again only variables that were found to significantly affect survival are included in the five models (A through E). Cambium survival was not significantly different between western redcedar, Engelmann spruce, and western white pine. These species are aliased so their coefficients are zero. Based on the p-values, the evidence that cambium survival of western hemlock and grand fir is greater than the aliased species is inconclusive. Survival was significantly greater in western larch and Douglas-fir. The depth of bark char is a powerful predictor of cambium condition. The deep bark char level is aliased. Survival was significantly lower beneath deeply charred bark and increased as charring became less severe. The only fuel variable found to be a significant predictor is the change in the number of 1,000-hour fuels. Note the p-value indicates there is only weak evidence that the change in the fuel load rating is a significant predictor of cambial mortality.

Summary and Conclusions

The results of this preliminary analysis demonstrate that supplemental protection is potentially useful for reducing cambium injury when burning partially cut stands containing a mixture of fire resistant and nonresistant species. The retardant treatment was the most effective, but the combined influence of heavy loadings of 100- and 1,000-hour fuels negated retardant's effectiveness. This is consistent with visual observations that indicated that retardants prevented

Table 7. Analysis of deviance table for the preliminary postfire model.

Model	Deviance	d.f.	LR[1]	d.f.	p-value
A: intercept	2341.96	1956			
B: A + species	1845.83	1952	495.54	4	0.0000
C: B + DBC	1080.54	1949	765.28	3	0.0000
D: C + fuels	1062.66	1947	17.88	2	0.0001
E: D + DBH	1046.83	1946	15.83	1	0.0000

----------Parameter estimates for model E----------

Parameter	coeff.	std. error	Wald stat.	p-value
Intercept	-5.8862	0.5097	-11.5475	0.0000
Species				
Douglas-fir	3.5656	0.2644	13.4838	0.0000
Western white pine	0.0000	-	-	-
Western hemlock	0.3820	0.2012	1.8983	0.0577
Western larch	4.1080	0.2653	15.4834	0.0000
Grand fir	0.6895	0.4301	1.6031	0.1089
Engelmann spruce	0.0000	-	-	-
Western red cedar	0.0000	-	-	-
Depth of bark char				
None	7.7621	0.4837	16.0463	0.0000
Superficial	4.9752	0.4226	11.7732	0.0000
Moderate	3.4936	0.3867	9.0350	0.0000
Deep	0.0000	-	-	-
Change # 1,000-hr.	-0.3839	0.1162	-3.3045	0.0010
Change fuel rating	-0.1312	0.0750	-3.3045	0.0802
DBH (cm)	0.0277	0.0070	3.9273	0.0001

---

[1] LR - Likelihood ratio statistic

moderate or lighter fuel loadings from burning but did not prevent heavy concentrations from burning. Future studies might do well to determine how the probability of burning changes with increasing fuel loading. The fuel removal treatment was only marginally more effective than burning unprotected trees. Fuel removal and retardant application could be applied ahead of time, whereas foam needed to be applied immediately before ignition. This presented logistical problems. Although we did not find the foam treatment as effective as retardant, the treatment has promise if more effective long-lasting foams can be developed. We had difficulty getting the foam to adhere to tree boles and it evaporated when nearby untreated fuels burned for long durations. Additional research into foams and their delivery systems could improve the potential of this treatment. Treatment costs were outside the scope of the present study but cost effectiveness should be considered in the future.

A qualitative descriptor of the degree of bark charring was a powerful indicator of cambium survival (Table 4). In the postfire model (Table 7), species was arbitrarily added before the degree of bark char. Additional analysis not reported here indicated that if bark char was added first, species would still be significant but would not have a large effect on predicted mortality. We also found strong trends in bark char across the range of changes in fuel load rating. These suggest the potential for developing better applications oriented models.

Additional analyses are being conducted to further quantify species/treatment/fuel loading interactions. For example, one analysis (not reported here) indicated that fuel load rating is only a slightly less precise indicator of potential cambium injury than measured fuel quantities. Such a model would have greater utility to managers who cannot afford the extensive fuel inventory needed to apply the models herein. So far we have found significant species interactions with a number of tree and fuel variables, but many of them are complex, difficult to interpret, and beyond the scope of this presentation. The lack of consistent relationships between important fuel and tree morphology variables suggests the need for further research into the factors controlling injury during burning. The models presented herein are useful for promoting further research but should not be considered for operational application.

Endnotes

[1] The use of trade or firm names in this paper is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

References

BISHOP, Y.M.M., S.E. FIENBERG, and P.W. HOLLAND. 1975. Discrete Multivariate Analysis: Theory and Practice. Massachusetts Institute of Technology Press, Cambridge, MA.

BROWN, J.K. 1974. Handbook for inventorying downed woody material. USDA For. Serv. Gen. Tech. Rep. INT-16. Intermt. For. and Range Exp. Sta.

BYTH, K., and G.J. McLACHLAN. 1980. Logistic regression compared to normal discrimination for non-normal populations. Aust. J. Stat. 22: 188-196.

CRAWLEY, D.R. 1979. Logistic discrimination as an alternative to Fisher's linear discrimination function. N.Z. Stat. 14(2): 21-25.

LANDWEHR, J.M., F. PREGIBON, and A.C. SCHOEMAKER. 1984. Graphical methods for assessing logistic regression models. J. Am. Stat. Assoc. 79: 61-71.

McCULLAGH, P., and J.A. NELDER. 1983. Generalized Linear Models. Chapman and Hall. New York.

PETERSON, D.L., and K.C. RYAN. 1986. Modeling postfire conifer mortality for long-range planning. Environ. Manage. 10(6): 797-808.

PRESS, S.J., and S. WILSON. 1978. Choosing between logistic regression and discriminant analysis. J. Am. Stat. Assoc. 73: 699-705.

REINHARDT, E.D., and K.C. RYAN. 1988. How to estimate tree mortality resulting from underburning. Fire Manage. Notes. 49(4): 30-36.

RYAN, K.C. 1981. Evaluation of a passive flame-height sensor to estimate forest fire intensity. USDA For. Serv. Res. Note PNW-390. Pacific NW For. and Range Exp. Sta.

RYAN, K.C. 1982. Evaluating potential tree mortality from prescribed burning. P. 167-169. In D.M. Baumgartner, ed, Proc. symp. on site preparation and fuels management on steep terrain. Wash. State Univ. Coop. Ext.

RYAN, K.C. 1983. Techniques for assessing fire damage to trees. P. 1-11. In J.E. Lotan, ed, Proc. symp. on Fire--Its Field Effects. Intermt Fire Council, Missoula, MT.

RYAN, K.C., and E.D. REINHARDT. 1988. Predicting postfire mortality of seven western conifers. Can. J. For. Res. 18: 1291-1297.

Prescribed Fire - A Cost Effective Control for White Pine Cone Beetle

D. D. WADE
U.S. Forest Service
Macon, Georgia

G. L. DEBARR
U.S. Forest Service
Athens, Georgia;

L. R. BARBER
U.S.Forest Service
Asheville, North Carolina

E. MANCHESTER
U.S. Forest Service
Murphy, North Carolina

Abstract

One of the most destructive seed insects of Eastern white pine (Pinus strobus) is the white pine cone beetle (Conophthorus coniperda). This pest can destroy entire seed crops. Early spring prescribed fire controlled this beetle in a North Carolina seed orchard, at considerably less cost than alternative chemical methods. Some seed trees were damaged but none have died. Pertinent life-cycle aspects of the beetle, level of control achieved, and fire behavior and effects are discussed. Preliminary operational guidelines for using prescribed fire to control the white pine cone beetle are presented.

Résumé

Les scolytes des cônes du pin blanc (Conopthorus coniperda) est l'un des insectes le plus destructeur des graines du pin blanc de l'est (Pinus strobus). Ce ravageur peut détruire des récoltes entières de graines. Un brûlage dirigé effectué au début du printemps a réussi à réprimer ce ravageur dans un verger à graines de la Caroline du Nord et a permis de réaliser des économies considérables comparativement aux autres méthodes de lutte chimique utilisées. Certains semenciers ont subi des dégâts mais aucun d'eux n'est mort. Certains aspects pertinents du cycle évolutif de ce coléoptère sont examinés ainsi que le degré de répression atteint et le comportement et les effets du feu. Des directives opérationnelles préliminaires sur l'utilisation du brûlage dirigé pour lutter contre le scolyte des cônes du pin blanc sont présentées.

Introduction

The white pine cone beetle (WPCB), Conophthorus coniperda (Schwarz) is the most damaging seed and cone insect of eastern white pine (Pinus strobus L.). In seed orchards, the loss of genetically improved seed can be particularly devastating. A worst case example was found in a 1988 damage survey of an Ohio seed orchard where the entire 1988 cone crop and over 90 percent of the 1989 cone crop (conelets) had been destroyed and the terminal shoots (the 1990 cone crop) were under attack by the WPCB (Barber, unpublished data).

The only effective insecticide is the systemic, carbofuran (Furadan®) (DeBarr et al. 1982). Over the past decade, a single winter application of this chemical has satisfactorily controlled the insect on the 26 ha white pine planting at the U.S. Forest Service Beech Creek Seed Orchard near Murphy, North Carolina. However, the recommended dosage is proportional to tree diameter, so the amount needed, and thus costs, escalate as trees grow. Furthermore, below-normal rainfall from January through early April is thought to limit insecticide uptake and translocation. Western North Carolina has been in a severe drought since 1984. The precipitation shortfall is about 1.8 m for the period 1984-1988 according to Wayne Swank (personal communication) of the Coweeta Hydrologic Laboratory, Franklin, NC.

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

Environmental concerns also continue to surface regarding this EPA approved chemical. Carbofuran was last applied at Beech Creek in 1985 at a cost of about $990 dollars per hectare. Approximately 11 ha were left untreated that year to assess the amount of beetle damage. On the untreated area, WPCB destroyed 92 percent of the seedcrop. This untenable level of damage prompted a reexamination of the beetle life cycle with an eye toward possible control options.

Adult WPCB overwinter on the ground in fallen cones (ODell and Godwin 1964). They emerge in the spring and fly into nearby white pines where they attack developing cones. They lay eggs as they proceed through several cones by early summer. Infested cones die and most fall to the ground unopened. The larvae feed on seeds and interior tissues of these dead cones. There is only one generation per year.

The WPCB thus spends 9-10 months of the year in fairly small dead cones in the litter beneath its host tree-- a habit that suggests prescribed fire as an effective control mechanism. Additional elements that allude to the potential of fire include: (1) short-term exposure to temperatures of 40-50°C is lethal to most insects, including the WPCB, and (2) seed orchards are routinely mowed to reduce fuel buildup and facilitate movement and seed collection.

USE OF FIRE TO CONTROL RELATED SPECIES

Mellish (1987) and Miller (1978) described the use of prescribed fire to control a related pest, the red pine cone beetle, *C. resinosae* Hopkins, in red pine (*P. resinosa* Ait.). There are, however, several important differences between the situation reported in Miller's work and the one encountered at Beech Creek. First, Miller used fire in natural stands that had been thinned to serve as seed production areas, whereas at Beech Creek the trees are all grafts and thus considerably more valuable. Second, red pine is much more fire resistant than white pine when mature (Wilson and McQuilkin 1969). According to Van Wagner (1970), both red and white pines are very susceptible to bole damage until the trees approach 30 cm. d.b.h. On the ramets at Beech Creek, graft unions are generally within one-third of a meter above ground. The bark above the grafts will remain thin, even after the trees attain considerable girth. Third, unlike the red pine seed production areas Miller studied, the Beech Creek seed orchard in the Southern Appalachians is on 30 percent slopes. The uphill sides of trees are much closer to the ground, and thus nearer a fire than would be the case on level ground. Finally, the red pine cone beetle overwinters in abscised vegetative buds while the WPCB overwinters in cones, which might provide more protection from fire.

The buds of both red pine and white pine are preset, which means that once the spring flush takes place, another flush will not take place until the following spring. Numerous studies have shown that complete defoliation during the summer usually results in death (Kulman 1965). Nonetheless, it was decided to attempt control of the WPCB with prescribed fire of very low intensity.

1987 Pilot Burn

The test was conducted on a 1 ha block containing about 150 trees. The ramets were 20 years old and averaged about 28 cm d.b.h. and 13 m in height. An adjacent area containing the same number of trees and a similar clonal layout was selected to serve as a check plot. Herbicide (Roundup®) had been used throughout the orchard in 1986 to control vegetation in a strip about 3 m wide within each row of trees. The heavy fescue sod between the rows had been mowed during the fall of 1986, but by March 6, 1987, the day of the burn, the succulent regrowth was about 13 cm tall. On the morning of the burn, the litter was raked back about 1 m from around each tree bole, exposing mineral soil. The debris was scattered to minimize the possibility of hot spots. The litter was raked from around only half the bole on 15 trees to evaluate this procedure.

Weather data were automatically recorded at the permanent weather station at the orchard office located within 1 km of the burn and at approximately the same elevation. The plot was ignited from a wetline at 12 noon, and burnout occurred about 45 minutes later. Burning conditions were: drybulb temperature 12°C, relative humidity 25 percent, and wind velocity SE at 5 km/h gusting to 10 km/h. The last recorded precipitation was 44.5 mm on Feb. 28 (7 days prior to the burn).

Fire damage to the seed trees appeared minor. Needles on one or more low branches on 15-20 trees were scorched but the buds were not damaged so the branches all refoliated. Pitch on the boles of 2 trees that had not been raked on one side caught fire but was quickly extinguished. All trees looked healthy the following spring.

WPCB mortality results exceeded expectations. Some infested cones were charred throughout, some partially charred, and some just scorched, but it made no difference. All beetles perished except for one sample of artificially placed cones that were extremely wet (moisture content 198% compared to the average of about 65%) in which 5 of 111 beetles survived.

1988 Operational Burn

BURNING PROCEDURES

The 1987 burn demonstrated the potential of fire to safely control the WPCB in eastern white pine. But questions remained regarding the practicality and costs of operational-size fires. The conelets present in the summer of 1987 suggested a bumper seed crop in 1988. The decision was thus reached to burn the full 26 ha planting of white pine in the orchard in the spring of

1988, including the 1 ha burned in 1987. The planting was comprised of 3 areas, each from a different seed source, and separated from one another by other species of seed orchard trees, or by oak-dominated hardwood forest. Because of the large investment tied up in each tree, there was little margin for error -- safety of the trees was paramount, but no guidelines existed except for the experience gained from the previous year. Moreover, the period between snowmelt and beetle emergence is fairly short and characterized by wide swings in the weather. Because the steep terrain was conducive to erosion, no permanent firelines were constructed.

The lower two whorls of branches were pruned from the white pines on all three areas during the fall of 1987 and the debris removed. Pruning left the pines with a clear bole up to about 2.5 meters and increased the distance between the ground and crown, thereby decreasing the chance of crown scorch during the burns. However, many of the pruning cuts bled profusely, resulting in a heavy flow of resin down the tree stems. The litter was raked from around each tree bole out to about a 1 m radius to help protect the tree stems and to reduce the chance of igniting these resin flows. Although the 1987 pilot burn showed that very little of the 2750 kg/ha litter (L) layer had to be consumed to achieve good WPCB control, increased forest floor consumption would not be harmful to the trees as long as the 15,000 kg/ha duff (F plus H layer) was damp enough to limit consumption of that layer.

A dry cold front passed through the area on Feb 29, and the decision was made to begin burning the following day even though the forecast predicted a very low minimum relative humidity. As long as the lower duff remained too wet to burn, the major concern about low humidity was from a fire control standpoint. If we saw that too much of the litter layer was being consumed as the humidity dropped during the day, or if easy control of the fire became questionable, the fire could be extinguished by one of the two tractor-mounted sprayers routinely used in the orchard or by a U.S. Forest Service pumper, all on site during the burn.

At 1030 hours on March 1, 1988, the first fire was ignited from a wetline along the highest edge of the area and allowed to back downhill past the first row of trees, and then across about 5 to 6 meters (rows were 9 m apart) of grass before reaching the heavy litter associated with the next downhill row of trees. Downhill rates of spread were predictably slow (roughly 20 m/h), and various modifications in the ignition plan were tested to find a procedure that would result in a faster burnout time without unduly increasing the potential of tree damage. Personnel patrolling the fire front with 19-liter backpack pumps to wet down resinous tree boles that appeared to be getting too hot (in fact several did ignite before being extinguished) were kept busy until an efficient firing pattern was developed. This pattern entailed ignition of the upper side of the area, letting the fire back down past the uppermost row of trees into the grass median between tree rows, then igniting the bottom of that grass strip. The upper edge of this second fire would head across the grass and meet the fire backing downhill while the lower edge would itself back downhill past the second row of trees. This process was repeated until the bottom side of the area was fired. Personnel with backpack pumps soon learned to anticipate potential problem trees and wet down the boles before the fire front arrived. Damage to individual tree crowns was generally minor (less than 10 percent) except in the draws, where convective heat was channeled. Crown damage was more extensive on trees in draws; the foliage on some was almost completely scorched.

Many of the mature open cones (moisture content 9%) were consumed, but the closed immature cones (moisture content 12%) containing the beetles were not. Moisture content of the cured grass and "L" layer averaged 13 percent at ignition, dropped to 8 percent by 1400 hours and recovered to 13 percent by 1845 hours. Duff moisture ranged from 16 to 33 percent. Much of the litter layer was consumed, but the duff layer remained to insulate the soil and tree roots. Some problems were experienced within the 1-m raked circles. Many eastern white pine roots were exposed when the litter was raked from around the trees. Because these large roots were at the surface, it was difficult to remove the duff. Raking was done several days prior to the burn, giving any remaining duff time to dry out. If these inter-root patches of duff were not wet-down before being reached by the fire front, they invariably ignited.

Flame lengths of backing fires averaged 0.15 to 0.25 m, and headfires 0.3 to 0.5 m. Backing fire flame zone width was less than 3 cm. The fire front backing downhill could not preheat fuels on these steep slopes, whereas the flame envelope moving uphill was close to the ground and preheated fuels ahead of it. Headfire flame zone width averaged 0.06 to 0.6 m, depending upon windspeed. Wind gusts frequently tilted the flames enough to make contact with the unburned fuel, causing ignition 0.4 to 0.6 m at a time rather than as a steady progression upslope. This process strongly influenced headfire rates of spread, which ranged from 0.36 to over 1.2 km/h. Fireline intensity also varied widely from about 100 to 850 kW/m. Flame residence time averaged about 7 to 9 seconds regardless of fire type. Burnout on the first area occurred at about 1245 hours. By this time the RH had dropped below 20 percent but no control problems were noted. About 90 percent of the area burned. Spotting was not a problem and no containment problems were encountered, primarily because of the light fuel loads between the tree rows.

The second area was ignited at 1400 hours using the procedure perfected earlier in the day. Much less crown scorch was incurred. Some of the duff remaining between tree roots in the raked circles was removed just prior to ignition of the area to eliminate this source of potential damage. Four of the 8 blocks in this second area were left unburned to serve as a control. Relative humidity reached a minimum of 14 percent and drybulb temperature peaked at 14°C at about 1530 hours. Fire behavior parameters increased slightly. Backing fire rate of spread increased to about 26 m/h and residence time decreased to 5 to 6 seconds. Average headfire rates of spread ranged from 0.22 to 0.3 km/h when flame contact did not occur and upwards of 1.1 km/h when flame contact took place. Maximum average flame length increased to 0.5 m for backing fires and 0.8 m for heading fires. Fuel consumption increased to over 50 percent and some infested cones were partially consumed. This area contained the plot burned the previous spring. Although litter fuels were very light, the herbaceous cover was complete and carried the fire well. Burnout of the last block on the second area was complete by 1930 hours.

The final area was ignited at 1015 hours the next day. Drybulb temperature reached 20°C and the relative humidity again dropped below 20 percent. Fire behavior was essentially the same as the previous day. Little crown scorch was noted but some tree boles ignited, primarily because an attempt was made to burn off several spur ridges at the same time resulting in too many lines of fire for the people with backpack pumps to effectively monitor.

TREE DAMAGE

Four weeks after the fires, a damage survey was conducted and trees on the first two areas placed in one of 4 crown scorch classes. Forty-nine trees on Area 1 and 6 on Area 2 were severely scorched (over 33 percent crown scorch), but all leafed out during spring flush. Most of the trees in this scorch class had less than 50 percent crown scorch, but even the 3 that lost more than 80 percent of their foliage survived. The moderate scorch class (10 to 33 percent) contained 94 and 32 trees on Areas 1 and 2, respectively. Seventy-eight trees on Area 2 suffered 1 to 10 percent crown scorch as did several hundred on Area 1. A total of 335 trees on the Area 2 burns were unscorched. Crown scorch on Area 3 trees was not mapped because a cursory survey turned up only a few trees in the moderate scorch class and none in the severe scorch class. One year after burning, scorched trees throughout the orchard appeared just as healthy as unscorched trees, except that their crowns looked thinner because the branches with heat-killed foliage contained only 1-year-old needles. Since the buds of eastern white pine are preformed, prescribed burns should be conducted before the spring flush. Otherwise, extensive scorch is likely to cause mortality.

Inspection of the trees 1 year after burning showed many had large patches of discolored (brown) surface bark which appeared to be dead. These patches were primarily on the uphill side and ranged from about 0.5 to 4 m above ground (precisely where heat from a fire would be concentrated). Discolored patches were also found on trees in the unburned blocks, but not as many of them. When heavily pruned, eastern white pine is prone to sunscald which could account for much of the damage. In addition, a mechanical tree shaker has been used for the past 5 years to dislodge seeds.

S. Oak (personal communication), U.S. Forest Service plant pathologist, believes that these discolored patches are simply a result of natural bark maturation, which begins first on the sides of the trees that are exposed to higher temperatures and drying by solar radiation. Pruning and burning simply accelerated the process. However, subsequent to this analysis, reference to fire-caused eastern white pine cambial injury was found in the literature (Olson and Weyrick 1987). Their research, based on several dozen fires over the past 15 years, shows heat injury is indicated by "...rusty red color and soft spongy feeling on the outer bark. If this red color completely encircles the stem, the tree will die." Some of the trees at Beech Creek are almost encircled and although they looked healthy 12 months after the March 1988 fires, the demands of bud break and foliage production this spring should determine the fate of these trees.

WPCB CONTROL

Analysis of cones collected before and after the burn showed that beetle populations had been decimated on all three areas. Nonetheless, the WPCB killed 66 percent of the cones on Area 1 in 1988. About twice as many cones were found to be beetle-killed on the unburned portion of Area 2 as on the burned portion. On Area 3, roughly 10 percent of the cones were attacked during the spring of 1988.

Several hypothese were developed to explain this cone mortality in light of the high level of WPCB control achieved on the burns. Nets are used to collect the seed crop each fall and infested cones are simply discarded at the edge of the area. Reexamination revealed that many of these piles of cones in Area 1 did not show any signs of scorch. The fire never reached these piles, apparently because the wetline was located uphill of them. In addition, a high beetle population exists in the naturally occurring eastern white pine adjacent to the orchard. These sources of beetles along with beetles in the unburned half of Area 2 were likely causes of the high incidence of attack in the burned areas. In spite of these losses, 1988 yielded a bumper crop of seed. Over 90 kg/ha were collected -- enough to meet the expected demand for the next 2 to 3 years.

Preliminary Prescribed Fire Guidelines

The first 2 years of burning have been a learning experience for all involved. The following guidelines have emerged from this field study for conducting future burns under eastern white pine ramets in the Beech Creek Seed Orchard.

1. Do not burn under conditions as severe as those used in 1988. Fire control was not a problem and the

pines apparently escaped serious damage, but less intense fires would have done just as good a job.

2. Burn all eastern white pine areas between snowmelt and at least 2 weeks prior to beetle emergence, which usually occurs about April 1st. Once greenup occurs, it becomes more difficult to back fires through the grass.

3. Rake the litter from a 1 m radius circle around each tree and off of exposed roots. Rake just prior to burning so any duff remaining inside the circle will not have the opportunity to dry out.

4. Use wetlines and not plowlines as firebreaks.

5. Begin burning in the morning as soon as, but not before, any dew or frost has evaporated. Shaded areas not yet reached by the sun may not burn. It is important that the fire covers the full area so all cones are heated.

6. Ignite the upper boundary with a line fire so that it backs downhill past the first row of trees. When the fire is 1 to 1.5 m past this first row, the torch person can bring the flank downhill along a wetline, make a 90 degree turn and string fire across the area several feet upslope of the second row of trees. This fire will head uphill to meet the initial backing fire and back downslope past the second row of trees. The process is continued until the lower boundary of the area is reached.

7. A wide range of weather conditions can be tolerated. Preferred conditions include adequate soil moisture (Keetch-Byram Drought Index below 250), fine-fuel moisture content between 8 and 20 percent, infested cone moisture content less than 65 percent, relative humidity 20 to 50 percent, and drybulb temperature below 15°C.

8. Low windspeed from a single direction would be ideal. Variable winds up to perhaps 5 to 6 m/sec can be easily accommodated as long as the burning boss makes appropriate adjustments in firing technique. Windspeed across ridgetops will likely exceed the 6 m windspeed registered at the orchard office weather station.

9. Complete consumption of the litter layer is a strong indicator that the fire should be extinguished. WPCB's will be killed by very low intensity fires unless the infested cones have an unusually high moisture content. The cones do not have to be consumed, simply scorching them will raise internal temperatures past the lethal threshold.

10. Both tractor-pulled and truck-mounted sprayers proved very effective. Foam is not necessary.

11. Backpack sprayers should be mandatory! Wetting tree boles is tiring but essential work. Individuals must be in excellent physical condition and self motivated to be most effective. The best policy would be to wet down each tree bole and all exposed roots in the cleared circle just prior to arrival of the fire front, rather than waiting to see if the resin or remaining duff catches fire and then trying to get close enough to extinguish the flames.

12. Whenever a line of fire is ignited across a draw, this topographic feature will act as a chimney to concentrate and channel heat up the draw. Any trees in the draw will thus have a much higher potential of being crown scorched.

13. These burns should have a minimal impact on air quality because of the light fuel loadings and lack of smoldering combustion.

Summary

The white pine cone beetle is one of the most destructive seed and cone insects in North America. It is not unusual to lose the complete eastern white pine seed crop to this pest. The systemic insecticide carbofuran effectively controlled this beetle on the Beech Creek Seed Orchard in western North Carolina until 1984, but thereafter its usefulness was drastically curtailed by costs and severe drought conditions. This prompted the "last resort" decision to use fire. When planning the first trial burn, no guidelines existed. Based on the literature, we were braced for the distinct possibility of severe tree damage including some mortality.

The gamble paid off. Even the few trees that suffered over 50 percent crown scorch appeared healthy 1 year after burning. We demonstrated that WPCB populations can be significantly reduced at a cost less than one tenth that of chemical control. We believe even higher levels of control can be achieved by making sure all infested cones are included in the areas to be burned.

References

DEBARR, G.L., L.R. BARBER, AND A.H. MAXWELL. 1982. Use of carbofuran for control of eastern white pine cone and seed insects. Forest Ecology and Management 4:1-18.

KULMAN, H.M. 1965. Effects of artificial defoliation of pine on subsequent shoot and needle growth. Forest Science 11(1):90-98.

MELLISH, S.B. 1987. The use of prescribed fire for control of the red pine cone beetle, (Conopthorus resinosae Hopkins) (Coleoptera:Scolytidae) in a New Brunswick red pine (Pinus resinosa Aiton) seed production area. M.S. Thesis, Univ. of New Brunswick, 120 pp.

MILLER, W.E. 1978. Use of prescribed burning in seed production areas to control red pine cone beetle. Environmental Entomology 7(5):698-702.

ODELL, T.M. AND P.A. GODWIN. 1964. White-pine cone beetle. USDA For. Pest Leafl. 83, 7 pp.

OLSON, D.P. AND R.R. WEYRICK. 1987. White pine management with prescribed fire. New Hampshire Agricultural Experiment Station Research Report Number 113. 15p. New Hampshire Agricultural Experiment Station, University of New Hampshire, Durham, NH

VAN WAGNER, C.E. 1970. Fire and red pine. Proceedings 10th Annual Tall Timbers Fire Ecology Conference. Fredericton, New Brunswick. August 20-21, 1970. p.211-219.

WILSON, R.W. JR., AND W.E. MCQUILKIN. 1969. Silvicultural characteristics of eastern white pine. USDA Forest Service Research Paper NE-13. 29p. Northeastern Forest Experiment Station, Broomall, PA.

Factors Affecting White Spruce (Picea glauca [Moench] Voss) Seed Germination On Burned Forest Litter

M.R. COYEA, V.J. LIEFFERS, P.M. WOODARD
University of Alberta, Edmonton, Alberta

Abstract

Seedbed temperatures and burned forest litter were studied because of their potential impact upon white spruce germination. In a field study, soil temperatures on an upland burned site in north-central Alberta were documented. Temperature extremes of 65°C on exposed sites, and 38°C on shaded sites were recorded. A factorial experiment in controlled laboratory conditions, tested the germination response of white spruce seed from two provenances, on four seedbed conditions (distilled water, fresh ash, leached ash and leachate from ash), in five regimes where temperatures were elevated for two hours (30°C, 35°C, 40°C, 45°C, 48°C) from a constant base temperature of 20°C. Germination percent decreased as temperatures increased. None of the seeds germinated at 48°C. Germination was lowest on fresh ash, and highest on distilled water for all temperature treatments. The number of days to fifty percent germination on burned forest litter increased as temperature increased. Chemical analysis of the soluble components of ash extracts suggested that the low responses on fresh and leached ash were not simply due to salinity, even though pH may have played a partial role.

Résumé

A la suite du brûlage de déchets de coupe, deux facteurs environnementaux ont été étudiés pour connaître leur impact potentiel sur la germination de l'épinette blanche. Ces facteurs étaient la température du lit de germination et la litière brûlée. Des données sur la température du sol en surface et la température de l'air ont été recueillies dans une station de haute terre du centre-nord de l'Alberta dans le cadre d'une étude sur le terrain. Des extrêmes de température de 65°C dans des stations exposées et de 38°C dans des stations ombragées ont été enregistrés. Une expérience factorielle a été effectuée en laboratoire dans des conditions contrôlées pour vérifier le taux de germination de graines d'épinette blanche provenant de deux endroits différents ensemencées dans des lits de germination soumis à quatre types de traitements (eau distillée, cendres fraîches, cendres lessivées et percolat de cendres) et à cinq régimes différents, les températures étant élevées pendant 2 heures (30°C, 35°C, 40°C, 45°C, 48°C) à partir d'une température de base constante de 20°C. Le pourcentage de germination diminuait à mesure que la température augmentait. Aucune graine n'a germé à 48°C. Les cendres fraîches présentaient le plus faible pourcentage de germination et l'eau distillée le plus fort pourcentage pour tous les traitements de température. Le nombre de jours pour atteindre une germination de 50% augmentait à mesure que la température s'élevait. Des analyses chimiques des composantes solubles des extraits de cendres laissent supposer que les faibles pourcentages degermination dans les cendres fraîches et lessivées n'étaient pas uniquement attribuables à la salinité, même si le pH peut y avoir un certain rôle.

Introduction

Re-establishing conifers after wild or prescribed fires is highly influenced by the resulting environmental conditions and the inherited traits of the seeds. Burning can significantly affect the surface energy balance (Hungerford and Bobbitt 1987, Oliver et al. 1987, Brand and Janas 1988) and the soil conditions (Raison 1979, Feller 1982). The magnitude of these effects can have a positive or negative effect on tree seed germination success (Woodard and Cummins 1987). The objectives of the study reported here were: (1) to document the range in soil temperatures during the 1987 field season, on a prescribed burn site, and (2) to determine if high temperatures of short duration and the presence of the ash or leachates from the ash have an impact on white spruce (Picea glauca [Moench] Voss) seed germination.

Study Area

The instrumented, field, study site was located 15 km southeast of Calling Lake, Alberta, Canada (113° 06' 30" W, 55° 05' 30" N). The site is considered to be in the Moist Mixedwood Subregion of the Boreal Mixedwood Region (Strong and Leggatt 1981). Aspen (Populus tremuloides Michx.) or balsam poplar (P. balsamifera L.) predominate in younger undisturbed forests. White spruce (Picea glauca [Moench] Voss) and black spruce (P. mariana [Mill.] B.S.P.) are the common conifers in older stands. White spruce predominates over black spruce on well-drained sites. The reverse is true on wetter sites.

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

In June 1984, the field site was disturbed by a tornado. Extensive blowdown and tree injury resulted from wind in excess of 200 km/h. Over 236,000 m^3 of wood was salvaged during the summer of 1985. On 22 August 1986, the site was burned according to prescription in an attempt to reduce site preparation costs. The Canadian Forest Fire Weather Index codes (Canadian Forestry Service 1984) at the time of ignition (1430 hrs) were: FFMC 85; DMC 51; DC 293; ISI 3; BUI 69; and FWI 10. Fuel loadings were not documented prior to or immediately following burning, therefore we have no knowledge of fire severity. At the inception of this study (spring 1987), the ash and residual organic layer varied from 0 to 5 cm in depth.

Methods

FIELD

Open, level sites, with uniformly charred surfaces were selected. Three replicates of soil temperatures were measured using thermocouples, at .5 cm below the soil surface under open and shaded conditions. Shaded microsites were created using white 30 x 30 cm horizontal platforms supported at 15 cm height. Temperatures were recorded every minute, and summarized as daily averages, maximum and minimum values using Campbell Scientific (Edmonton, Alberta) programmable data-loggers. The sampling period was from 11 June to 12 September 1987. New vegetation within and surrounding the immediate vicinity of each microsite was removed throughout the season, thus eliminating the effects of shading.

SEED GERMINATION IN CONTROLLED ENVIRONMENTS

Six replicates of 40 seeds from two white spruce seed provenances, collected locally, were randomly sown to 9 cm diameter petri dishes lined with Kimpak[1] (Woodard and Cummins 1987) or Kimpak and various types of ash residue. Burned residues used in this experiment were produced by combusting 90% by weight of surface materials collected from a white spruce - balsam poplar site in north-central Alberta. Seeds sown to Kimpak and distilled water served as the control treatment. Treatment 2 consisted of 30 ml of distilled water plus 1.50 g of unleached ash, which is equivalent to 2.36 t/ha of residue left after 90% fuel consumption of 23.6 t/ha of forest biomass. Treatment 3 was 30 ml of leachate from ash on Kimpak. This leachate was prepared by collecting the filtrate after 10 g of ash on Whatman #2 filter paper was washed 10 separate times with 25 ml of distilled water. The washed residue from preparing the previous treatment was used as the seedbed media in Treatment 4. This treatment consisted of 30 ml of distilled water plus 1.466 g of leached ash, which is equivalent to 1.5 g of fresh ash minus the weight lost during leaching.

Seeds were stratified on seedbeds for 21 days at 3-5°C following International Seed Testing Association (1985) rules. Five separate growth chambers in a phytotron were used for this experiment. Air temperatures were held constant at 20°C for 22 hrs in all chambers and elevated to 30, 35, 40, 45 or 48°C for 2 hrs daily in one of the five chambers used. These temperature regimes were selected to artificially recreate temperature regimes of burned field sites with peack daytime heating. The 30°C chamber was considered the control temperature treatment. The photoperiod was 16 hr day and 8 hr night. Petri dishes were randomly positioned, then repositioned every second day during the 21 day incubation period. Seedbeds were daily rehydrated using distilled water. Germination checks began seven days after stratification. Seeds were classed as germinates and removed from dishes when the radicle extended four times the length of the seed.

STATISTICAL ANALYSIS

A three-way factorial analysis of variance was conducted based upon two seedlots, four substrates, four temperature regimes and six petri dishes per treatment. The arcsin transformation of germination percentages was used to satisfy the assumption of the normal distribution (Steel and Torrie 1980). Scheffe's multiple comparison test was then applied.

Results

Soil temperatures were significantly higher in exposed burned surfaces when compared to shaded surfaces ($p < 0.05$). In addition, soil temperatures > 30°C occurred more frequently under exposed microsites (Figure 1). For example, maximum soil

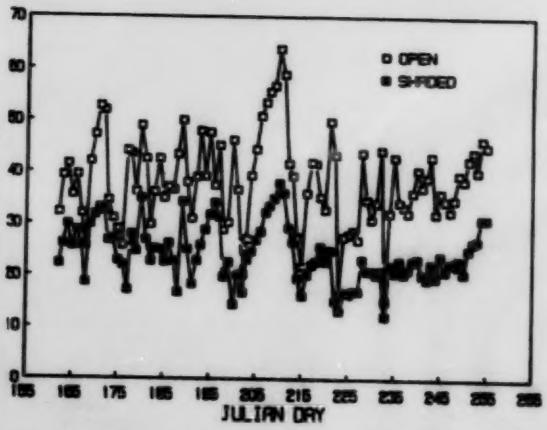


FIG. 1. A record of 0.5 cm deep average daily maximum soil temperatures measured during the 1988 field season for open and shaded plots (n=3 observations/data point).

---

[1] Kimpak is a multilayered absorbent material, produced by Seedburo Equipment Company, (Kimberly Clark), Chicago, Illinois.

temperatures were > 30°C for 78 days during the 93 day field season; and of those, temperatures were > 40°C for 42 days, and for eight of those days the temperature exceeded 50°C. Under shaded conditions, soil temperatures never exceeded 40°C and were > 30°C on only 16 days. Clearly, shade significantly reduced the maximum soil temperatures documented on these burned surfaces.

Generally, germination success was inversely related to changes in ambient air temperature (Table 1). This condition was true for all treatments except seeds germinated on Kimpak moistened with distilled water (control). Seeds did not germinate when ambient air temperatures reached 48°C, hence this treatment regime was dropped from further analysis.

Both temperature and substrate treatments had a significant effect on germination of white spruce seed regardless of seed provenance used (Table 2). Germination was best for the distilled water treatment of the two lower temperatures (Table 1). However, seeds sown on Kimpak and moistened with the leachate solution did not have significantly lower germination ($p < .05$) in the 30°C and 35°C temperature regimes (Table 1). Than the distilled water treatment when temperatures were lower. Both ash substrates significantly reduced germination success compared to the distilled water treatments.

Generally, seeds from the two seedlots responded similarly when subjected to different substrates and temperatures but the magnitude of the response was significantly different ($p = 0.00004$). There was a significant interaction between seedlot and substrate ($p = 0.044125$, Table 2). Differences were greatest for the control treatment and least for fresh ash (Figure 2). Seeds from seedlot B germinated better than those from seedlot A with the exception of fresh ash subjected to 45°C.

The average seed germination duration was 14 days. Generally, as temperature increased, the number of days to 50% germination (R50) increased. But this result is only significant when the 30°C regime is compared to the 45°C regime (Coyea 1988).

Table 1. Scheffe's multiple comparisons of the means of percent germination for seedlot A and B combined at the different temperature and substrate regimes [2].

Substrate	Temperature Regime (°C)			
	30	35	40	45
Fresh Ash	35.8a(c)	28.5a(b)	2.9a(a)	0.8a(a)
Leached Ash	57.7b(b)	52.9b(b)	3.8a(a)	2.7ab(a)
Leachate	72.1bc(b)	67.3bc(b)	15.6b(a)	14.4bc(a)
Distilled Water	78.3c(b)	84.4c(b)	35.2c(a)	30.0c(a)

[2] Comparisons were made first by temperature, on each column independently (letters are not bracketed). A second group of comparisons were made for each substrate medium for each row (letters are bracketed). Means followed by similar letters were not significantly different ($p < 0.05$).

Table 2. Summary of analysis of variance for percent germination data of white spruce.

	F-Ratio	DF	Prob.
Seedlot	17.91	1.0	0.00004
Temperature	469.89	3.0	0.00000
Substrate	213.52	3.0	0.00000
Seedlot*Temperature	1.37	3.0	0.25435
Seedlot*Temperature	2.76	3.0	0.04425
Temp*Substrate	3.67	9.0	0.00034
Seedlot*Temp*Substrate	0.80	9.0	0.62134

Note: The 48°C treatment was not included in this analysis.

Discussion

It is well known that high temperatures are lethal to plant tissue. Fraser (1971) found that white spruce seed germination decreased dramatically when temperatures exceeded 38°C. Arnott (1973) found the average optimum temperature for boreal conifer germination to be 24°C. While it may be that some boreal sites are too cold for optimum forest growth (Viereck and Schandelmeir 1980), sites after fire may be too hot at some time during the day. This is evident, particularly for sites that are devoid of shade. Also, depending on the frequency of high temperature, the probability of white spruce seed survival may be quite low.

The ashbed environment also adversely affects seed germination. Germination was clearly lowest on leached and fresh ashbeds. The results of this experiment contradicted reports for other tree species which reported that ashbeds and their chemical constituents had either no effect or a positive effect on tree seed germination (deKeijzer and Hermann 1966, Woodard and Cummins 1987). But there is evidence that organics released from fire residues can affect seed germination (deKeijzer and Hermann 1966, Keeley and Pizzorno 1986, Woodard and Cummins 1987). The reasons for these apparent anomalies are further discussed in Coyea, Lieffers and Woodard (manuscript in preparation).

There are several management implications associated with the results of this work. First, high soil temperatures occur on exposed sites burned sites in the boreal forest.

These extreme temperatures are common and can be lethal to seed germination. Therefore, steps should be taken to ameliorate high soil temperatures after burning if white spruce seed germination is desired. Second, ash, even after leaching, reduced germination success. Therefore, seeding should be delayed until precipitation has leached and eroded the ashbeds. Third, the variation in germination success suggests that multiple provenances should be used when reseeding an area, unless managers have identified those seedlots which are capable of tolerating burned seedbeds.

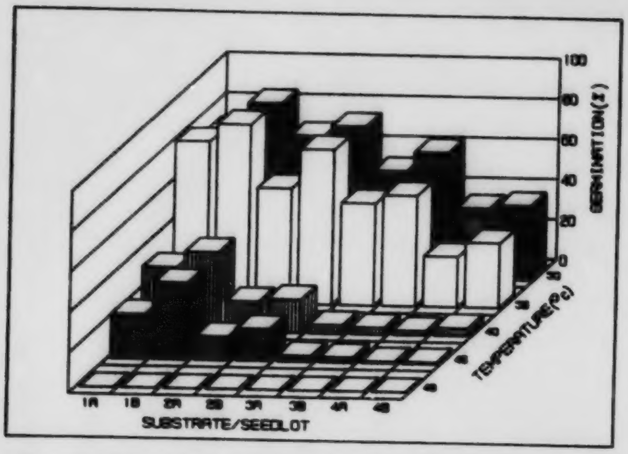


FIG. 2. The percent germination response for two seedlots (A, B), subjected to five different air temperatures while sown on four different substrates (1=distilled water-control, 2=ash leachate, 3=leached ash, and 4=fresh ash). (n=6 replicates of 40 seeds).

Literature Cited

ARNOTT, J.T. 1973. Germination and seedling establishment. pp. 55-66. In J.H. Cayford. (ed.). G. Direct seeding symposium. Dept. of the Environ. Can. For. Serv. Pub. No. 1339. Ottawa.

BRAND, D.G., AND P.S. JANAS. 1988. Growth and acclimation of planted white pine and white spruce seedlings in response to environmental conditions. Can. J. For. Res. 18: 320-329.

CANADIAN FORESTRY SERVICE. 1984. Tables for the Canadian Forest Fire Weather Index. 4th ed. Environ. Can., Can. For. Serv. Forest. Tech. Rep. No. 25.

COYEA, M.R. 1988. Factors affecting white spruce (Picea glauca) seed germination on burned forest litter. M.Sc. Thesis. University of Alberta. Edmonton, Alberta. 91 p.

DEKEIJZER, S., AND R.K. HERMANN. 1966. Effects of charcoal on germination of Douglas-fir seed. Northwest Sci. 40: 155-163.

FELLER, M.C. 1982. The ecological effects of slash burning with particular reference to British Colombia: a literature review. B.C. Min. For. Land Manag. Rep. No. 13.

FRASER, J.W. 1971. Cardinal temperatures for germination of six provenances of white spruce seed. Can. For. Serv. Pub. 1290. 10 p.

HUNGERFORD, R.D., AND R.E. BABBITT. 1987. Overstory removal and residue treatments affect soil surface, air, and soil temperature: Implications for seedling survival. USDA For. Serv. Res. Pap. INT-377.

INTERNATIONAL SEED TESTING ASSOCIATION. 1985. International rules for seed testing 1985. Seed Sci. & Technol. 13: 299-355.

KEELEY, S.C., AND M. PIZZORNO. 1986. Charred wood stimulated germination of two fire-following harbs of the California chaparral and the role of hemicellulose. Amer. J. Bot. 73: 1289-1297.

OLIVER, S.A., H.R. OLIVER, J.S. WALLACE, AND A.M. ROBERTS. 1987. Soil heat flux and temperature variation with vegetation, soil type and climate. Agric. For. Meteorol. 39: 257-269.

RAISON, R.J. 1979. Modification of the soil environment by vegetation fires, with particular reference to nitrogen transformations: A review. Plant and Soil 51: 73-108.

STEEL, R.G.D., AND J.H. TORRIE. 1980. Principles and procedures of statistics: A biometrical approach. (2nd. ed.) McGraw-Hill Book Company. Toronto.

STRONG, W.L., AND K.R. LEGGATT. 1981. Ecoregions of Alberta. Alberta Energy and Natural Resources. Edmonton.

VIERECK, L.A., AND L.A. SCHANDELMEIER. 1980. Effects of fire in Alaska and adjacent Canada - a literature review. U.S. Dept. Int. Bur. Land Manage. Alaska State Office. B.L.M.-Alaska Technical Report 6.

WOODARD, P.M., AND G. CUMMINS. 1987. Engelmann spruce, lodgepole pine and subalpine fir seed germination success on ash bed conditions. Northwest Sci. 61: 233-238.

Estimation of Nutrient Loss to the Atmosphere from Slashburns in British Columbia

M. C. FELLER
Faculty of Forestry, University of B.C.
Vancouver, British Columbia

Abstract

A research program was established in 1980 with an objective of developing methods of estimating and predicting nutrient loss to the atmosphere from slashburns in British Columbia. Nutrient (N, P, S, Na, K, Mg, and Ca) losses during both broadcast slashburns and small experimental plot burns have been measured. Attempts have been made to relate nutrient losses from coastal B.C. slashburns to fuel load and fuel consumption parameters and to the codes and indices of the Canadian Forest Fire Weather Index (FWI) System. The best estimator of nutrient loss appears to be forest floor depth of burn. Regression equations developed for slashburns in coastal British Columbia conifer slash which estimated nutrient loss as a function of depth of burn could be reliably extrapolated to two other slashburning situations in B.C. in the case of N, but not in the case of K and Ca and possibly not in the case of P and S. Reliable equations to predict nutrient losses from the coastal B.C. slashburns could generally not be developed.

Résumé

Un programme de recherche mis sur pied en 1980 avait pour objectif d'élaborer des méthodes pour estimer et prévoir la quantité d'éléments nutritifs dissipée dans l'atmosphère par des brûlages dirigés en Colombie-Britannique. Les pertes d'éléments nutritifs (N, P, S, Na, K, Mg et Ca) se produisant lors de brûlages dispersés et de petits brûlages expérimentaux de parcelles ont été mesurées. Nous avons tenté de corréler les pertes d'éléments nutritifs à des paramètres de la biomasse de combustible et de consumation de combustibles ainsi qu'aux codes et aux indices de la Méthode canadienne de l'Indice Forêt- Météo. Le meilleur estimateur de la perte d'éléments nutritifs semble êtrel'épaisseur de la litière consumée par le feu. Les équations de régression développées pour les brûlages dirigés vers les conifères du littoral de la Colombie-Britannique qui estimaient la perte d'éléments nutritifs en fonction de l'épaisseur du brûlage pouvaient être extrapolées avec fiabilité à deux autres situations de brûlage en C.-B. dans le cas de N, mais pas dans le cas de K et Ca et possiblement pas dans le cas de P et S. En général, des équations fiables pour prédire les pertes d'éléments nutritifs de brûlages dirigés vers le littoral de la C.-B. ne pouvaient être développées.

Introduction

The prescribed burning of slash from tree cutting operations (slashburning) is important in British Columbia where over 50,000 ha is currently burned annually. The effects of slashburning on forest productivity have been a matter of considerable debate (e.g. Feller 1982). Ecosystem nutrient status is an important determinant of forest productivity so that the effects of slashburning on ecosystem nutrient status must be studied to understand the effects of slashburning on forest productivity.

Although slashburning tends to cause an increase in available nutrients in the soil, at least initially, it generally causes a loss of total nutrients from an ecosystem, due to volatilization and upward movement of particulates to the atmosphere, and increased leaching through the soil (e.g. Feller 1982). The significance of such losses has been demonstrated in Australia, where they have resulted in decreased productivity of Pinus radiata plantations on poor sandy soils (e.g. Woods 1980). Productivity declines as a result of nutrient losses from slashburning will be more serious on poorer sites, but the magnitude of the losses that different ecosystems can sustain without exhibiting lowered productivity, is currently unknown.

A research program to address this question was established by the author in British Columbia in 1980. One objective of this program is to develop methods of estimating and predicting nutrient losses to the atmosphere, as such losses account for most of the losses resulting from burning (e.g. Feller 1982). This objective is being achieved by quantifying nutrient losses and relating them to measured fuel parameters and to the codes and indices of the Canadian Forest Fire Weather Index (FWI) System. These codes and indices are indicators of fuel moisture content, available fuel, and fire rate of spread and intensity and should, intuitively, be related to nutrient losses to the atmosphere. Both operational slashburns and small experimental plot burns have been studied. The present report summarizes results from all burns studied to date.

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

Methods

STUDY AREA

The study has been carried out primarily in the Coastal Western Hemlock zone of coastal B.C. although more recently, data have been collected in the Sub-Boreal Spruce and Engelmann Spruce - Subalpine Fir zones (Krajina 1969). The present report discusses data from the Coastal Western Hemlock zone and includes data from only one slashburn outside this zone - from the Sub-Boreal Spruce zone.

Sixteen of the 23 broadcast slashburns studied were conducted within the University of British Columbia (U.B.C.) Malcolm Knapp Research Forest near Haney, located 40 km east of Vancouver, and within Vancouver's water-supply watersheds - Capilano, Seymour, and Coquitlam - located within 30 km north and east of Vancouver. One set of 6 burns was conducted at Salvus, located 60 km west of Terrace in central western B.C. The small plot burns were all conducted in the U.B.C. Research Forest. One slashburn in the Sub-Boreal Spruce zone was conducted near Joel Lake, approximately 100 km east of Smithers in west central B.C.

The 16 Coastal Western Hemlock zone burns near Vancouver ranged in size from 2 to 25 ha. They have been conducted at elevations of 100-900 m a.s.l. on a variety of aspects and slopes, but generally on shallow (<1 m) coarse-textured mineral soils with 10-20 cm deep mor and moder forest floors. The six Salvus burns, each approximately 1 ha in size, were conducted on relatively deep fine-textured alluvial soils with mull forest floors consisting only of a thin (1-2 cm) litter (L) layer.

The Joel Lake burn was 53 ha in size and was conducted on a north-facing gently sloping cutblock at an elevation of 900-1000 m a.s.l. The cutblock contained two groups of ecosystems - the well drained upland mesic group with 5-12 cm deep mor forest floors overlying fine textured mineral soils, and the imperfectly drained lower slope subhygric groups with 10-30 cm deep moder forest floors overlying fine textured mineral soils.

Forests in the Coastal Western Hemlock zone study areas are dominated by the conifers - Tsuga heterophylla (western hemlock) and Thuja plicata (western red cedar) with Picea sitchensis (sitka spruce) common at low elevations near the coast and to the north, Pseudotsuga menziesii (Douglas-fir) common at low elevations inland to the south, and Abies amabilis (amabilis fir) and Chamaecyparis nootkatensis (yellow cedar) common at higher elevations. Early successional forests in this zone, particularly on the more fertile soils, are often characterized by hardwood species, primarily Alnus rubra (red alder), with lesser amounts of Populus balsamifera ssp. trichocarpa (black cottonwood) and Betula papyrifera (western white birch). The U.B.C. Research Forest and Vancouver watershed burns were conducted in April through October in logging slash ≤ two years old from mature conifer forests, while the Salvus burns were conducted in August in three-month-old slash from an early successional hardwood forest which was knocked down to convert the area to a conifer plantation.

Forests in the Sub-Boreal Spruce zone study area are dominated by Picea glauca x engelmannii (hybrid white spruce), Abies lasiocarpa (subalpine fir), and Pinus contorta (lodgepole pine) with a small amount of Populus tremuloides (trembling aspen) scattered throughout. The forest in the Joel Lake study area was logged during winter then slashburned the following October. Further details about the study areas are available in Feller (1988), Taylor (1987), and references therein.

FIELD SAMPLING

For all burns, nutrient losses to the atmosphere were estimated by determining the quantity of nutrients in all organic material above the mineral soil surface both before and immediately after a burn prior to the deposition of any type of water on the site, and assuming that the difference between these quantities was accounted for by losses to the atmosphere. This procedure involved quantifying the different types of organic material present (dead woody materials, understory vegetation, and forest floor) and analysing subsamples of each type for nutrient concentrations, both before and after a burn.

For each broadcast or small plot burn the codes and indices of the FWI System were calculated using data from an on-site or nearby (within 4 km) weather station. All FWI System codes and indices were calculated using the most recent version of the system (Van Wagner and Pickett 1985). The Fine Fuel Moisture Code of the system was adjusted for the slope and aspect of the burned area and the time of the burn according to the tables given in Alexander et al. (1984).

1. Broadcast slashburns

The mass of dead woody materials >1 cm diameter was determined using the line intersect technique with total transect lengths of 450-900 m per clearcut. The only exception was at Salvus where the mass of dead woody materials from the knocked down hardwoods was estimated from a) biomass regression equations relating woody biomass to tree d.b.h. and b) measurements of d.b.h. of all trees in 10 x 10 m square plots in the forests prior to their knocking down. Regression equations were developed for each of the tree species present (red alder, cottonwood, sitka spruce, and western hemlock). Relative densities were determined for each size class (1.1 - 3.0, 3.1 - 5.0, 5.1 - 7.0, 7.1 - 12.0, and >12 cm diameter) of dead woody material for each species present, and separately for older partially decayed wood, both before and after burning. These densities were used with the line intersect data to calculate woody material fuel loads. For all burns in conifer slash, the postburn intersects were run along the same lines as the preburn ones.

The quantity of fine woody fuels <1 cm diameter, and also of understory vegetation, was estimated by destructive sampling of 20 to 30 one m^2 or 0.5 m^2 plots randomly located within each clearcut, immediately prior to burning and the same number of such plots, but with different locations, immediately after burning.

The quantity of forest floor was estimated from 20 to 50 excavations (20 x 20 cm square) to mineral soil randomly located within each clearcut. Two measurements of forest floor depth were made on opposite sides of each excavation. The bulk density of the surface 10 cm of forest floor (or less for shallower forest floors) was estimated from an additional 20 to 50 randomly located excavations (20 x 20 cm square). Forest floor consumption was estimated by multiplying the average depth of burn (measured using 100 - 540 depth of burn pins (Trowbridge et al. 1986) per clearcut) by the average preburn bulk density of the surface 10 cm (or less) of forest floor and converting to an area basis.

The percentage of a clearcut actually burned was determined from measurements along transects, at least 500 m long. In some instances (when <90% of a clearcut was burned) it was necessary to stratify a burned clearcut into unburned and burned sections and assume that the postburn quantity of organic material in the unburned section was identical to the average preburn quantity of organic material per unit area in the entire clearcut.

2. Small plot burns

Full experimental details for the small plot burns are given in Feller (1988). These are briefly summarized here. In June and July 1984, slash was hand-cleared from a 0.3 ha area with a relatively uniform and undisturbed forest floor lying within a clearcut in the U.B.C. Research Forest. Slash materials were sorted by species and size class and known amounts were added to fifty 2.25 m^2 plots separated into 10 groups of 5 plots. The 5 plots within each group received either 10 kg/m^2 of Douglas-fir or western red cedar/yellow cedar slash, or 4, 10, or 18 kg/m^2 of western hemlock slash. This was done to test the effects of species origin of the slash and slash load on nutrient loss during burning.

Each group of 5 plots was burned on a different day characterized by different burning conditions, as indicated by the codes and indices of the FWI System. Pre- and postburn forest floor sampling, postburn slash sampling, and postburn measurements of depth of burn provided estimates of slash and forest floor consumption.

LABORATORY PROCEDURES

All organic material samples were oven-dried at 70°C for dry mass determinations. Multiple oven-dried samples (at least 5) from each category of organic material sampled pre- and postburn (i.e. each size class of each species of dead woody material; each component - leaves, branches, and stems - of each tree species in the Salvus area; each group of understory plants - shrubs, ferns, herbs, and mosses; and the forest floor - entire forest floor and the surface 10 cm preburn, and the postburn forest floor down to a preburn depth of 10 cm) were ground to pass a 1 mm mesh sieve then subjected to the following chemical analyses:

1. Total N and P - prior to 1987 by semimicro Kjeldahl digestion followed by colorimetric analysis of NH_4^+ and $PO_4^=$ in solution using a Technicon Autoanalyzer II. Since 1987 by Parkinson and Allen digestion (Parkinson and Allen 1975) followed by colorimetric analysis of NH_4^+ and $PO_4^=$ in solution using a Technicon TRAACS 800 continuous-flow analysis instrument.
2. Total K, Na, Mg, and Ca - prior to 1987 by a dry ashing procedure. Following dissolution of the ash, cation concentrations in solution were measured by atomic absorption spectrophotometry. Since 1987 the dry ashing procedure has been replaced with Parkinson and Allen digestion.
3. Total S - prior to 1987 by a Leco SC-32 sulphur determinator. Since 1987 by a Fisher model 475 sulphur analyzer.

Thus, data from the following burns given in Table 1 were obtained using a Parsinson and Allen digestion: CQ-1, CP-29, CP-30, CP-31, CP-32, and the 6 SAL burns.

Ground samples were stored up to six months and digestion solutions, up to two months (frozen) prior to analysis. The accuracy of the chemical anlayses was checked by frequent calibration of the analytical instruments with standards, analysis of plant material with known chemical concentrations (reference samples), and analysis of blank (water) samples that had been put through the digestion procedure. In addition, a duplicate anlaysis was conducted on every fortieth last material sample. From these checks, it is considered that all chemical analyses were accurate to within 5% of the true value.

DATA ANALYSIS

1. Broadcast burns

The 16 broadcast slashburns assessed in the U.B.C. Research Forest and the Vancouver watersheds formed the major dataset which was analysed separately. This analysis was done to determine a) which fuel and FWI System variables were best correlated with nutrient losses, and b) if precise equations could be developed which either predicted or estimated nutrient losses using the measured fuel and FWI System variables. The variables were thus split into two groups - a) those which could be used to predict nutrient losses prior to any burning (preburn forest floor depth and fuel loads and the 6 FWI System codes and indices - Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC), Drought Code (DC), Initial Spread Index (ISI), Buildup Index (BUI), and Fire Weather Index (FWI)), and b) those which could be used to estimate nutrient losses from a slashburn that had already occurred (fuel consumption parameters).

Plots were first made of the dependent variables (nutrient losses) against the independent ones (fuel and FWI System variables). When these plots indicated no visually obvious curvilinear relationships, linear correlation analysis was used to determine the correlation coefficients between each of the dependent and the various independent variables. Stepwise multiple linear regression analysis was then conducted to determine the best-fit equation which either predicted or estimated nutrient loss. The independent variables selected for inclusion in each analysis were the 3-5 variables which were best correlated with the nutrient loss but which were not significantly correlated with one another. The best-fit regression equations were determined by selecting equations with one or two variables based on their statistical significance, coefficients of determination, and standard errors of the estimates.

Whether or not the equations developed for the major dataset could be extrapolated to other situations was assessed by graphically comparing the results of the small plot, Salvus, and Joel Lake burns with those of the major dataset.

2. Small plot burns

Correlation analysis and analysis of variance, as described in Feller (1988), were used to determine which fuel consumption variables were best related to nutrient loss and if the species origin of slash or slash load influenced nutrient loss.

Results and Discussion

Some fuel, fuel consumption, and FWI System parameters for the broadcast slashburns studied, are given in Table 1. Preburn slash loads generally ranged from 10 to 30 kg/m^2 for all areas, while total preburn fuel loads generally ranged from 20 to 50 kg/m^2 for the conifer slash areas and 10 to 20 kg/m^2 for the hardwood slash. Forest floor depths of burn ranged from 0.1 to 6.4 cm for the conifer slashburns, and appear typical of the values measured for slashburns in western North America (e.g. Brown et al. 1985, Little et al. 1986, Ottmar et al. 1985, Macadam 1987). Slash consumption ranged from around 1 to 10 kg/m^2 and total fuel consumption ranged from around 1 to 20 kg/m^2, which also appear typical of slashburns in western North America (e.g. Brown et al. 1985, Little et al. 1986, Macadam 1987). Results for the small plot burns are discussed in detail in Feller (1988).

Nutrient losses to the atmosphere from the broadcast slashburns in conifer slash tended to decrease in the order N > Ca > S > K > P, Mg > Na (Table 1), which is essentially identical to that found for the small plot burns (Feller 1988). For the hardwood slashburns, the order was similar but S losses were relatively less. This is probably associated with the fact that forest floor consumption made a greater contribution to nutrient losses in the conifer than in the hardwood slashburns and that a greater proportion of the total nutrient losses from the conifer slashburns came from forest floor consumption than from slash consumption in the case of S (usually 80-100% from the forest floor) than in the case of the other nutrients (usually 60-85% for N, 30-75% for P, 20-60% for K, 60-85% for Mg, and 20-50% for Ca) except Na, for which losses were generally too small to allow meaningful calculations to be made.

Nitrogen losses exceeded those of the other nutrients and ranged over almost two orders of magnitude, from 10 to almost 1000 kg/ha. Beese (MacMillan Bloedel Ltd. - Pers. com. 1988) has recently measured N losses from a high impact operational slashburn in coastal B.C. of around 1300 kg/ha from the forest floor alone. Little and Ohmann (1988) found N losses from the forest floor alone from 33 broadcast slashburning treatments in western Washington and Oregon, ranged from 0 to 666 kg/ha with over 80% of the losses falling within the range 150-650 kg/ha. In a study of 4 other broadcast slashburning treatments in western Oregon, Little and Klock (1985) found total N losses ranged from 223 to 571 kg/ha. It would thus appear that slashburns in coastal B.C. would typically cause N losses of 200-800 kg/ha, with an upper limit of around 1500 kg/ha. Correlations between estimated nutrient losses and the fuel and FWI System variables studied suggested that none of the prediction variables were well correlated with nutrient loss, with the exception of preburn slash load, large slash load, and total fuel load with S loss (Table 2). This contrasts strongly with the results for the estimation variables, all of which, with the exception of fine fuel consumption, were significantly correlated with nutrient loss for each nutrient (Table 2). The variable best correlated with nutrient loss was forest floor depth of burn.

No significant correlations were found between nutrient loss and the FWI System codes and indices. The FFMC was the only FWI System variable which exhibited consistently positive correlations, and in fact was the FWI System variable best correlated, with nutrient loss. This result is not easy to explain since the FFMC was poorly correlated with those variables that were best correlated with nutrient loss ($r = 0.30$, -0.08, -0.10, and 0.16 for depth of burn, slash consumption, large slash consumption, and total fuel consumption, respectively). It was also poorly correlated with fine fuel consumption ($r = 0.05$). However, not too much should probably be read into the correlations between FFMC and nutrient loss since they are still not significant.

As depth of burn was the variable best correlated with nutrient loss, and work elsewhere has suggested that the FWI System variables which relate to forest floor moisture content - namely the DMC (Chrosciewicz 1978a, 1978b, Van Wagner 1972) and

Table 1. Estimated nutrient losses and some fuel, fuel consumption, and Fire Weather Index System parameters for broadcast slashburns assessed in B.C.

Burn	Nutrient loss							Preburn slash load (kg/m²)	FFMC	DMC	DC	ISI	BUI	FWI	Forest floor depth of burn** (cm)	Total Slash Consumption (kg/m²)	Total Fuel Consumption (Kg/m²)
	N	P	S	K	Na	Mg	Ca										
	(kg/ha)																
Conifer slash in CWH zone																	
H-74	982	16	n.m.***	37	n.m.	29	154	21.9	79	14	263	1.5	25	3	4.8	11.1	15.8
H-81	488	8	n.m.	17	n.m.	7	87	31.9	81	19	318	2	32	5	3.4	8.6	12.5
H-82	10	2	n.m.	0	1	0	4	24.6	74	8	193	2.5	15	3	0.1	0.6	0.7
H-83U	537	6	35	16	0	16	62	8.7	77	37	255	3	54	10	3.0	3.7	6.7
H-83L	580	6	38	19	0	17	64	11.3	76	34	242	1.5	51	5	3.2	4.8	8.0
H-86	154	11	17	11	0	8	30	7.8	81	8	147	3	14	4	0.8	0.8	1.9
CQ-1 (3-27)	376	24	55	44	0	23	90	25.5	89	17	40	8	17	10	1.9	2.0	4.5
CQ-2 (3-38)	768	74	76	62	1	44	185	22.2	92	14	109	6	21	10	5.1	6.2	12.8
CQ-3 (3-35)	331	27	42	36	0	19	85	17.3	81	7	35	2.5	9	2	2.3	2.8	5.0
CQ-4 (3-33)	439	35	50	41	1	24	113	17.4	81	31	64	1.5	31	3	3.8	3.9	7.4
CQ-5 (OR-3)	662	49	71	76	4	37	204	25.0	80	18	335	1.5	33	3	4.9	12.1	17.3
CP-29	822	77	100	74	9	48	211	27.4	82	13	37	2.5	14	3	6.4	9.7	16.5
CP-30	675	58	73	54	1	38	152	18.4	95	26	53	2	25	18	4.3	5.8	11.5
S-85	663	14	48	48	0	39	185	17.7	87	24	52	4	24	7	3.7	4.9	10.9
CP-31	325	23	54	50	0	23	108	20.5	70	10	38	1.5	12	1	2.9	7.0	9.1
CP-32	561	50	72	74	1	37	169	31.6	75	9	32	1.5	11	1	3.7	9.1	13.4
Hardwood slash in CWH zone (Salvus)																	
SAL-1	365	35	25	135	4	29	316	12.5	83	19	308	3	33	8	≤2	8.5	8.9
SAL-9	404	36	30	157	3	29	359	19.9	88	19	308	3	33	8	≤2	6.8	7.0
SAL-14	261	23	19	109	2	18	244	14.7	88	19	308	3	33	8	≤2	4.8	5.1
SAL-22	327	20	33	165	2	27	334	19.1	88	19	308	3	33	8	≤2	6.9	7.2
SAL-25	218	2	16	82	3	16	196	21.0	84	11	275	2.5	20	4	≤2	4.6	4.8
SAL-28	195	11	14	81	3	13	167	12.0	84	11	275	2.5	20	4	≤2	2.9	3.1
Conifer slash in SBS zone (Joel Lake)																	
JL-M*	551	53	87	61	n.m.	d.s.+	242	14.7	82	14	363	3	26	6	3.0	8.0	10.6
JL-S*	324	50	71	36	n.m.	d.s.	226	18.0	82	14	363	3	26	6	1.9	9.1	11.1

* Calculated from data in Taylor (1987).

**Preburn forest floor depth = 7.2 - 17.8 cm for conifer slash in CWH zone, 1-2 cm for Salvus and 8.1 cm for JL-M and 24.0 cm for JL-S.

***n.m. = not measured.

+d.s. = data suspect so not used.

Conifer slashburns are identified as follows:

H = U.B.C. Research Forest at Maney, CQ = Coquitlam watershed, CP = Capilano watershed, S = Seymour watershed, JL-M = Joel Lake mesic site, JL - S = Joel Lake subhygric site.

the BUI (Brown et al. 1985, McRae 1980, Muraro 1971) - are related to forest floor consumption, it was expected that DMC, BUI and also DC would be better related to nutrient loss than was found. These three FWI System variables were poorly correlated with depth of burn in the present study (r = 0.21, 0.00 and 0.16 for the DMC, DC, and BUI, respectively). This might be explained by the influence of other factors on the relationship between depth of burn and the three FWI System variables. These factors could include type of slash fuel, forest floor structure, and soil moisture regime (Chrosciewicz 1978a, 1978b, McRae 1980) as well as fire duration (Ottmar et al. 1985, Sandberg 1980).

In the present study, depth of burn for the broadcast burns was significantly ($P < 0.01$) correlated with total slash consumption, large slash consumption, and the square root of large slash consumption (r = 0.80, 0.77, and 0.84, respectively). The square root of the mass of large slash consumption is related to woody fuel diameter reduction, and hence fire duration (Ottmar et al. 1985, Sandberg 1980), through the relationship - mass = (density) x (volume) where volume is a function of the square of the diameter ($v=\sum\pi\ d^2/4\ L$). Thus, the results of the present study seem consistent with those of Ottmar et al. and Sandberg, suggesting that surface fire duration and heat load are important determinants of depth of burn which should be considered as well as forest floor moisture content. It is also worth noting that the relationships developed between depth of burn and the DMC or BUI of the FWI System have not always been very close. These relationships have been determined empirically using regression analysis. The derived regression equations could not always explain much of the variation in th depth of burn, having r^2 values of 0.04 to 0.8 (Chrosciewicz 1978a, 1978b) and 0.21 to 0.59 (McRa 1980). Muraro (1971) gave no statistics for his equation but a linear regression analysis of his data produced an equation with an r^2 value of 0.32.

The results from the small plot burns were broadly consistent with those from the broadcast slashburns in that depth of burn and slash consumption were generally better correlated with nutrient loss than were the FFMC, DMC, DC, and BUI of the FWI System, and depth of burn was better correlated with slash consumption variables than it was with the FFMC, DMC, DC, and BUI (Feller 1988). However, greater restrictions on the small plot burn dataset (only 10 different burning days, mean depths of burn of only 0.1 - 3.8 cm, and the lack of attainment of equilibrium combustion rates which would occur in larger broadcast slashburns) prevent a closer comparison with the broadcast slashburn dataset.

In light of the preceding discussion, it is not surprising that the best equations that could be developed to predict nutrient loss were not as good as those developed to estimate such loss (Table 3). The variable which appears in the best estimation equations was invariably depth of burn, which was able to explain 42-83% of the variation in nutrient loss (based on coefficients of determination). Three variables appeared in the best prediction equations - preburn total slash load, preburn fine slash load, and the FFMC of the FWI System. As was found for the small plot burns (Feller 1988) total slash consumption increased with preburn slash load ($r = 0.54$, significant at $P < 0.05$). This relationship, together with the generally high correlations between nutrient loss and total slash consumption (Table 2) can account for the appearance of total slash load as a variable in most of the prediction equations. The appearance of FFMC in these equations is difficult to explain, as discussed above. Preburn fine slash load, the third variable appearing in the prediction equations, was not significantly correlated with any other variables studied, except fine slash consumption. Fine slash consumption was weakly correlated ($r = 0.46$ significant at $P < 0.10$) with depth of burn, which might explain the appearance of fine slash load in the equations. However, with the exception of the equation for S, the prediction equations could explain approximately 50% or less of the variation in nutrient losses. Thus, they can not be used with much confidence at present.

The broadcast burns were conducted in slash coming from several tree species and in areas containing more than one ecosystem. The small plot burns indicated that species origin of the slash can significantly affect nutrient loss (Feller 1988). Data from Taylor (1987) summarized in Table 1 suggest that nutrient losses are less in wetter (JL-S in Table 1) than in drier (JL-M in Table 1) ecosystems, due presumably to lower forest floor consumption in the wetter ecosystems as a result of moister fuels there. These factors, in addition to the inherently high variability in many ecosystem components (e.g. in forest floor structure or chemistry) and the many opportunities for measurement errors in the procedures used to estimate nutrient losses, can account for the relatively low coefficients of determination and relatively high standard errors of the estimates of the equations given in Table 3.

The question arises as to whether or not one can extrapolate the equations given in Table 3 to other slashburning situations. The equations were developed for broadcast slashburns in coastal conifer slash only. To determine if they could be applied to other types of slashburns, data from the Salvus and Joel Lake area slashburns, respectively, were compared to those from the coastal conifer slash.

This was done by plotting nutrient loss as a function of depth of burn. For each nutrient, the individual data points, the regression line, and the 99% confidence limits are given (Figure 1). Superimposed on each graph are the two data points obtained from Joel Lake and a rectangle, within which the Salvus results lie. Discrete data points cannot be given for Salvus, because depth of burn was not measured there. However, the forest floor was 1 to 2 cm deep. Consequently, depth of burn would have varied from 0 to 2 cm, delineating 2 sides of the rectangle. The other 2 sides were delineated from the maximum and minimum nutrient losses measured among the 6 burns. Comparing the different datasets, it can be seen that P, S, and Ca losses were relatively higher for the Joel Lake burns, whereas K and Ca losses were relatively higher for the Salvus burns (Figure 1). These results can be attributed to differences between the 3 groups of burns in a) the species composition of the slash being burned (Feller 1988), b) the chemical composition of the slash and forest floor materials (nutrient concentrations in slash and forest floor materials were generally higher for the Joel Lake and Salvus burns than for the coastal conifer burns), and c) the ignition patterns used in the different burns (the Salvus and Joel Lake burns were convection burns ignited using a centre fired ignition pattern which may have produced a relatively more intense fire with relatively more turbulence and fuel consumption than the mixed flank and backing fires which characterized each of the coastal conifer slash burns - total fuel consumption in relation to the depth of burn for the Joel Lake and Salvus burns, was relatively high compared to that for the coastal conifer burns).

The data from the small plot burns were also compared to those of the coastal conifer slashburns in Figure 1. This was done by placing the 50 small plot burns into 7 groups such that all burns within a group had a similar depth of burn which lay within 0.3 cm of the group mean, then plotting the mean nutrient loss for each group as a function of its mean depth of burn. There was generally good agreement between the results from the small plot burns and those of the coastal conifer slashburns, particularly for the two relatively volatile nutrients - N and S - suggesting that the relationship between N and S loss and depth of burn is independent of the size of the slashburn. Of interest is the fact that the results from all sets of burns - coastal conifer, small plot, Joel Lake, and Salvus - appear consistent in the case of N (Figure 1), suggesting that the same equation can be used to

Table 2. Correlations between nutrient loss and fuel and Fire Weather Index System variables.

Fuel/FWI System parameter / Nutrient	Correlation coefficient N	P	S	K	Na	Mg	Ca
Prediction variables							
Preburn forest floor depth	-0.01	-0.07	0.40	0.17	0.15	0.02	0.21
Preburn slash load	0.19	0.38	0.82**	0.47	0.47	0.27	0.43
Preburn large slash load (>7 cm diameter)	0.15	0.37	0.81**	0.45	0.46	0.25	0.41
Preburn fine slash load (<1 cm diameter)	0.63**	-0.12	-0.02	0.11	-0.01	0.37	0.37
Preburn total fuel	0.23	0.24	0.72**	0.40	0.35	0.28	0.45
FFMC	0.36	0.47	0.28	0.29	0.04	0.47	0.38
DMC	0.28	-0.18	-0.21	-0.16	-0.16	0.02	-0.02
DC	0.12	-0.41	-0.26	-0.39	0.01	-0.39	-0.20
ISI	0.10	0.33	0.21	0.15	-0.14	0.28	0.12
BUI	0.27	-0.32	-0.28	-0.30	-0.14	-0.15	-0.13
FWI	0.22	0.19	0.09	0.00	-0.19	0.21	0.07
Estimation variables							
Depth of burn	0.93**	0.74**	0.92**	0.79**	0.63*	0.87**	0.91**
Slash consumption	0.79**	0.51*	0.81**	0.70**	0.62*	0.65**	0.80**
Large slash (>7 cm diameter) consumption	0.72**	0.52*	0.74**	0.72**	0.63*	0.63**	0.79**
Fine slash (<1 cm diameter) consumption	0.74**	0.05	0.26	0.29	0.08	0.51*	0.52*
Total fuel consumption	0.89**	0.64**	0.89**	0.78**	0.62*	0.80**	0.91**

* Significant at $P < 0.05$.
**Significant at $P < 0.01$.

Table 3. Best regression equations developed to predict and to estimate slashburning-induced nutrient losses to the atmosphere from fuel and Fire Weather Index System parameters.

Nutrient loss (L) is expressed above as a function of Fine Fuel Moisture Code (FFMC), preburn fine slash (<1 cm diameter) load (FSLD), preburn total slash load (SLALD), and depth of burn (DB).

Nutrient	Regression Equation	r^2	SE
a) Prediction			
N	$L = -773.24 + 325.52\ \text{FSLD} + 12.63\ \text{FFMC}$	0.51**	187.7
P	$L = -135.24 + 1.27\ \text{SLALD} + 1.71\ \text{FFMC}$	0.36*	21.1
S	$L = -43.52 + 2.44\ \text{SLALD} + 0.64\ \text{FFMC}$	.72**	12.7
K	$L = 9.67 + 1.53\ \text{SLALD}$	0.22*	21.7
Na	$L = -1.98 + 0.17\ \text{SLALD}$	0.22*	2.3
Mg	$L = -61.51 + 10.46\ \text{FSLD} + 0.96\ \text{FFMC}$	0.34*	12.3
Ca	$L = -246.43 + 3.69\ \text{SLALD} + 3.56\ \text{FFMC}$	0.33*	55.7
b) Estimation			
N	$L = 43.47 + 141.39\ \text{DB}$	0.83**	105.7
P	$L = -7.17 + 10.95\ \text{DB}$	0.52**	17.7
S	$L = 10.17 + 13.02\ \text{DB}$	0.77**	11.0
K	$L = 3.63 + 11.07\ \text{DB}$	0.56**	16.3
Na	$L = -1.85 + 0.95\ \text{DB}$	0.42*	1.9
Mg	$L = 0.50 + 7.38\ \text{DB}$	0.71**	7.9
Ca	$L = 0.19 + 34.99\ \text{DB}$	0.79**	29.6

* regression equation is significant at $P < 0.05$.
** regression equation is significant at $P < 0.01$.

r^2 is the coefficient of determination.
SE is the standard error of the estimate.

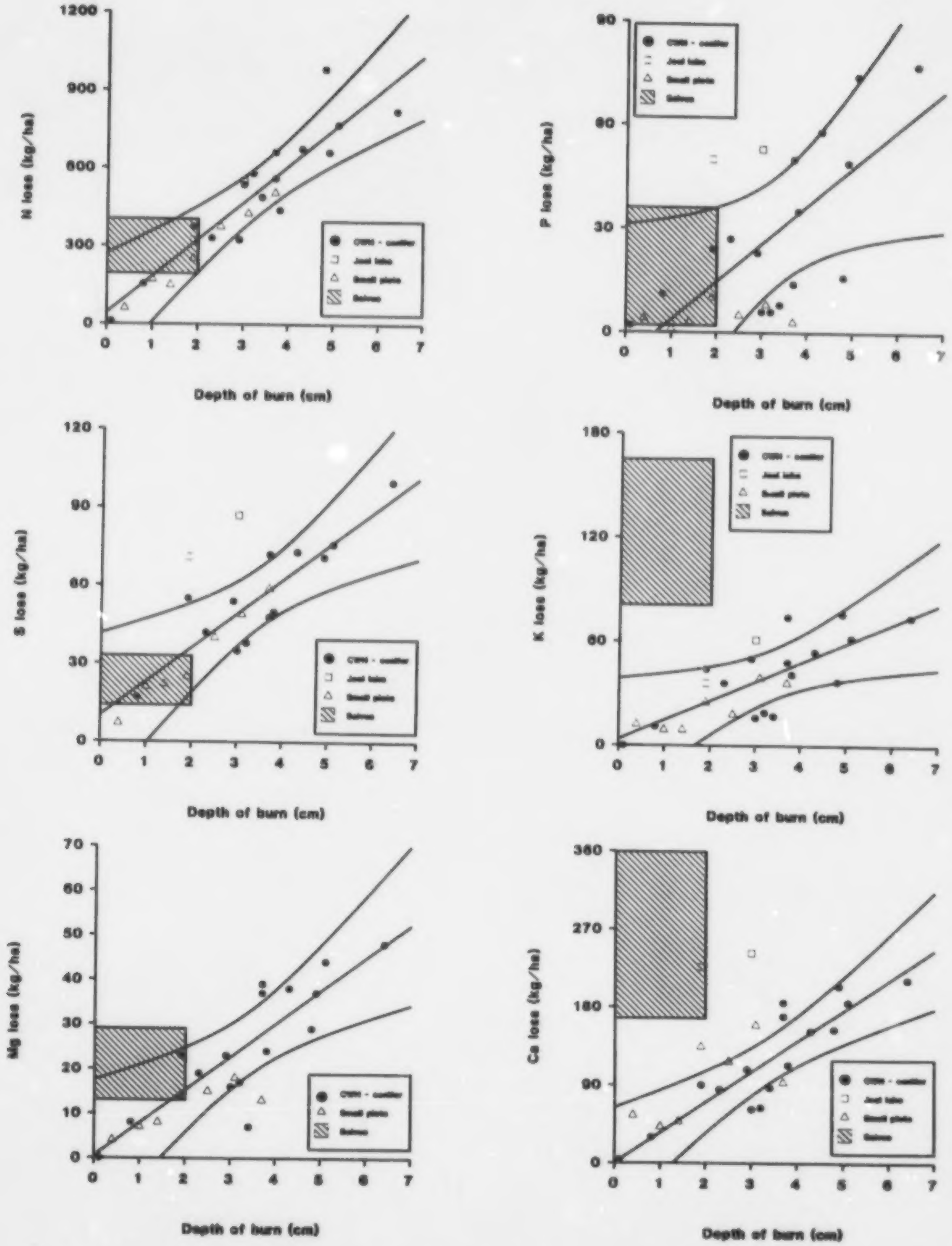


FIG. 1. Nutrient loss as a function of depth of burn for the burns studied. The regression line and its 99% confidence band are given for the coastal conifer slashburn dataset (CWH-conifer).

estimate N loss for a variety of burning situations. This does not appear to be possible for K and Ca, however, and it is uncertain whether or not it is possible for P, S, and Mg. These results are consistent with those of Raison et al. (1985) who found that, of N, P, and Ca percentage losses to the atmosphere from vegetation fires, those of N were best correlated to the proportion of organic matter lost. This relationship was a linear one, and applied to a very wide range of burning conditions throughout the world.

This suggests that the estimation equations developed for the coastal conifer slashburn dataset can not all be reliably extrapolated to different burning situations. The cause of this, whether differences in organic matter distribution and chemical composition or differences in ignition method and type of burn, or differences in other factors, is the subject of continuing studies.

Acknowledgements

The assistance of B. Blackwell, H. Carré, D. Conly, L. Fitzsimonds, A. Gorley, C. Holland, H. Jones, S. Kemsley, J.P. Kimmins, K. Klinka, M. Klinka, A. Macadam, A.B. McGee, B. McLeod, A. Pearson, C. Penfold, P. Quay, S.W. Taylor, R. Trowbridge, K.M. Tsze, K. Turner, M. Valenius, M. Van Arem, V. Venner, B. Wong, and J. Zwierink with various aspects of the study is gratefully acknowledged. The author wishes to thank J. Walters, and D. Munro and staff of the U.B.C. Malcolm Knapp Research Forest, and G. Joyce and other forestry staff of the Greater Vancouver Watershed District for valuable field assistance. Slashburning operations were conducted by staff of the U.B.C. Malcolm Knapp Research Forest, the forestry section of the Greater Vancouver Watershed District, B.C. Forest Service staff in the Kalum and Morice Forest Districts, and staff of Northwood Pulp and Timber Co. in Houston. The study has been supported by funds from NSERC of Canada, employment programs of Employment and Immigration Canada, the Canada-B.C. Forest Resources Development Agreement, the B.C. Forest Service, Forestry Canada, the University of B.C., and the Science Council of B.C.

References

ALEXANDER, M.E., B.D. LAWSON, B.J. STOCKS, AND C.E. VAN WAGNER. 1984. User guide to the Canadian Forest Fire Behavior Prediction System: Rate of spread relationships. Interim Edition. Can. For. Serv.

BROWN, J.K., M.A. MARSDEN, K.C. RYAN, AND E.D. REINHARDT. 1985. Predicting duff and woody fuel consumed by prescribed fire in the northern Rocky Mountains. USDA For. Serv. Res. Pap. INT-337, Interm. For. Ran. Exp. Sta.

CHROSCIEWICZ, Z. 1978a. Slash and duff reduction by burning on clear-cut jack pine sites in central Saskatchewan. Can. For. Serv. Info. Rep. NOR-X-200, Nor. For. Res. Cen.

CHROSCIEWICZ, Z. 1978b. Slash and duff reduction by burning on clear-cut jack pine sites in southeastern Manitoba. Can. For. Serv. Info. Rep. NOR-X-199, Nor. For. Res. Can.

FELLER, M.C. 1982. The ecological effects of slashburning with particular reference to British Columbia: a literature review. B.C. Min. For. Land Manage. Rep. No. 13.

FELLER, M.C. 1988. Relationships between fuel properties and slashburning-induced nutrient losses. For. Sci. 34:998-1015.

FELLER, M.C., J.P. KIMMINS, AND K.M. TSZE. 1983. Nutrient losses to the atmosphere during slashburns in southwestern British Columbia. P. 128-135 In Proc. Seventh Conf. Fire and For. Meteor., Fort Collins, Co., Amer. Meteor. Soc., Boston, Ma.

KRAJINA, V.J. (ed.). 1969. Ecology of forest trees in British Columbia. P. 1-147 In Ecology of Western North America, Vol. 2, No. 1, Dept. Botany, University of B.C., Vancouver, B.C.

LITTLE, S.N., AND G.O. KLOCK. 1985. The influence of residue removal and prescribed fire on distributions of forest nutrients. USDA For. Serv. Res. Pap. PNW-338, Pac. NW For. Ran. Exp. Sta.

LITTLE, S.N. AND J.L. OHMANN. 1988. Estimating nitrogen lost from forest floor during prescribed fires in Douglas-fir/western hemlock clearcuts. For. Sci. 34:152-164.

LITTLE, S.N., R.D. OTTMAR, AND J.L. OHMANN. 1986. Predicting duff consumption from prescribed burns on conifer clearcuts in western Oregon and western Washington. USDA For. Serv. Res. Pap. PNW-362, Pac. NW Res. Sta.

MACADAM, A.M. 1987. Effects of broadcast slash burning on fuels and soil chemical properties in the Sub-Boreal Spruce zone of central British Columbia. Can. J. For. Res. 17:1577-1584.

MACMILLAN BLOEDEL LTD. 1988. Personal Communications.

McRAE, D.J. 1980. Preliminary fuel consumption guidelines for prescribed burning in Ontario slash fuel complexes. Can. For. Serv. Rep. O-X-316, Great Lakes For. Res. Cen.

MURARO, S.J. 1971. Prescribed-fire impact in cedar-hemlock logging slash. Can. For. Serv. Publ. No. 1295, Ottawa.

OTTMAR, R.D., S.N. LITTLE, S.N. AND J. OHMANN. 1985. Predicting duff reduction to reduce smoke from clearcut slash burns in western Washington and western Oregon. P. 139-144 In L.R. Donoghue and R.E. Martin, eds., Proc. Eighth Conf. Fire and For. Meteor., Detroit, Mi., Soc. Amer. For. Bethesda, Md., SAF Publ. 85-04.

PARKINSON, J.A., AND S.E. ALLEN. 1975. A wet oxidation procedure for the determination of nitrogen and mineral nutrients in biological material. comm. soil sci. Plant Anal. b:1-11.

RAISON, R.J., P.K. KHANNA, AND P.V. WOODS. 1985. Mechanisms of element transfer to the atmosphere during vegetation fires. Can. J. For. Res. 15:132-140.

SANDBERG, D.V. 1980. Duff reduction by prescribed underburning in Douglas-fir. USDA For. Serv. Res. Pap. PNW-272, Pac. NW For. Ran. Exp. Sta.

TAYLOR, S.W. 1987. Initial effects of slashburning on the nutrient status of two Sub-Boreal Spruce zone ecosystems. M.Sc. thesis, University of B.C., Vancouver, B.C. 138 p.

TROWBRIDGE, R., B. HAWKES, A. MACADAM, AND J. PARMINTER. 1986. Field handbook for prescribed fire assessments in British Columbia: logging slash fuels. B.C. Min. For. Land Manage. Handbook No. 11. B.C. Min. For. and Can. For. Serv.

VAN WAGNER, C.E. 1972. Duff consumption by fire in eastern pine stands. Can. J. For. Res. 2:34-39.

VAN WAGNER, C.E., AND T.L. PICKETT. 1985. Equations and FORTRAN program for the Canadian Forest Fire Weather Index System. Can. For. Serv., For. Tech. Rep. 33, Ottawa.

WOODS, R.V. 1980. An investigation into the relationship between fire and nutrient depletion leading to decline in productivity between rotations of Pinus radiata plantations in South Australia. Woods Forest Dept., South Aust., Miscellaneous Pap. 37 p.

Institutional Constraints Affect Prescribed Burning Costs Variability: Preliminary Findings

A. GONZÁLEZ-CABÁN AND L.F. BEDNAR
Forest Service, U.S. Department of Agriculture
Riverside, California

Abstract

Prescribed burning costs are extremely variable, even under similar site conditions. Such cost variability and the continuous shrinkage of Forest Service budgets make it necessary to identify and understand the causes of variability. To describe and quantify the relative effect of institutional constraints, managerial, and physical factors on prescribed burning costs, a questionnaire was administered in person to fire and fuel managers in the USDA Forest Service's Northern and Pacific Northwest Regions. Some changes in prescribed burning costs were due solely to changes in institutional constraints. Contrary to our expectations, burn objective was not a significant factor. Unit size appears to have a larger effect on burn costs than does either change in slope or unit shape, which increases the amount of burn perimeter relative to the area burned. Costs per acre demonstrate economies-of-scale. The significance of ANOVA terms involving professional and managerial factors mean that these factors also have a direct relationship with prescribed burning costs.

Résumé

Les coûts entrcûnés par les brûlages dirigés sont êtremement variables, même dans des conditions similaires. Compte tenu de cette grande variabilité des coûts et de la diminution continue des budgets du service des forêts, il est essentiel d'identifier et de comprendre la cause de cette variabilité. Un questionnaire fût administré en personne aux gestionnaires de combustibles et l'incendies des régions du nord et nord-ouest pacifique du service forestier du USDA afin de décrire et quantifiér l'effet relatif sur les coûts de brûlage des contraintes institutionnelles et des facteurs physiques et de gestion. Certaines modifications dans les coûts de brûlages dirigés étaient uniquement reliées aux modifications des contraintes institutionnelles. L'objectif du brûlage n'était pas un facteur significatif, contrairement à nos attentes. La grandeur de l'unité semblerait avoir un plus grand effet sur les coûts reliés au brûlage que la modification de la pente ou la forme de l'unité, qui augmente le montant du périmétre du brûlage relativement à la superficie brûlée. Les coûts par acre démontrent des économies de grandeur. La signification des termes ANOVA, qui implique des facteurs professionels et des facteurs de gestion signifie que ces facteurs sont directement liés aux coûts des brûlages dinigés.

Introduction

Fuel treatment costs are extremely variable, even under similar site conditions, and may exceed their proposed benefits (economic and noneconomic). Broadcast burning costs on the Willamette and Lolo National Forests, for example, range from $60 per acre to $1,500 per acre (McKetta and Rich 1982). Prescribed burning costs in residual fuels of ponderosa pines in Northern Arizona ranged from less than $3 per acre to over $30 per acre (Wood 1988). On the Lolo National Forest, benefits of fuel treatments designed specifically for fire hazard reduction will rarely exceed the cost of the treatment. This conclusion by Wood (1979) held true even under his most optimistic comparisons of benefits, and could apply to much of the northern Rockies. With such large cost variability and continuous shrinkage of USDA Forest Service budgets, it is necessary to identify and understand the causes of the variability, and to make fuel treatment expenditures more predictable and cost effective.

The cost of prescribed fire is a function of the physical site, institutional, and managerial variables. Most fuel economics research has emphasized the analysis of physical site variables and their relationships to fire costs (e.g., Bunnell 1982, González-Cabán and McKetta 1986, McKetta and Rich 1982, Rich 1984). Site parameters alone do not explain most of the variability in prescribed fire costs, and some authors have recommended the inclusion of institutional and managerial variables, and measurement of their variability (González-Cabán and McKetta 1986, Rich 1984).

Institutional variables affecting prescribed fire costs take the form of rules, regulations, and management directives, such as smoke emission standards or mopup

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

standards, set by the Forest Service and other controlling agencies. Such protocol restricts the treatment alternatives available to managers.

Managerial variables incorporate the human, personal, and technical factors in planning and conducting the burns. Technical factors include selection of firing technique and ignition device, unit design, burn objective, and performance standards. Personal factors include items such as technical education, experience, and risk posture.

Individual differences in management philosophy, experience, risk posture, and skills affect the variability of prescribed burning costs (González-Cabán and McKetta 1986, Wood 1988). Loveless et al. (1982) concluded that burning costs analysis could be improved by emphasizing the variability in manager's decisions for a given prescribed burn situation.

The Forest Service objective to minimize escapes, for example, is evident in the mopup standards mandated for summer burning. Even though the objective of minimizing escapes is not explicit, the imposition of stringent mopup standards without reference to site conditions or economic efficiency indirectly transmits the objective to fire managers. With this implicit objective in mind, fire managers may use excessive resources during the burn because they perceive that the long-term benefit of preventing burn escapes has a higher value to the agency than an alternative that may be economically efficient.

In response to a series of prescribed burn escapes in the late 1970's, the Forest Service's Washington Office developed policies that specified any fire escape as unacceptable, created stricter burning and planning requirements, and reduced levels of acceptable risks (Bunnell 1982). These policies emphasize that minimization of wildfires is the primary consideration, making cost effectiveness or project efficiency a secondary criterion. Minimization of wildfires and cost minimization are not necessarily mutually exclusive goals, but when the policies get transformed into burning regulations at the forest level, the two appear to conflict. Little analysis of the tradeoffs between escape risk and burning costs have been done.

An example of this transformation is evident in the Forest Service's Northern Region summer burning mopup classification. Each class prescribes a different level of intensity and is directly related to the risk of an escape after the burn has been executed (Bunnell 1982). The cost difference for mopup category 1 (100 percent mopup) and mopup category 2 (perimeter mopup) can be almost $300 per acre (Bunnell 1982, Rich 1984). In Rich's (1984) study, one Ranger District could have saved, all other considerations aside, an estimated $110,094 for the 354 acres burned under mopup category 1 by executing the burns under a mopup category 2. This additional cost could be considered the mopup regulation cost to the District. This "institutional" constraint cost could have been greater if some of the mopup 1 burns could have been executed under a mopup 3 category (little to no mopup). The increased risk of escape was not quantified.

We hypothesize that the Forest Service target objectives for fire managers to eliminate fire escapes and eliminate deviations from stated burn-plan objectives causes prescribed burning costs to be high. If our hypothesis is correct, replacing these objectives with ones that emphasize cost-effectiveness could substantially reduce burning costs. The present objectives appear to be imbedded in mandated fire control regulations, fire control emphasis in training sessions, and evaluations of fuel treatment achievements. They may substitute excessive risk aversion to fire escapes for rational selection of alternatives in the mind of fire managers. Extreme institutionalized aversion to fire escapes communicates that the cost of any escape is infinitely high and makes cost-inefficient burn prescriptions automatic. Managers regularly assume "worst case" fire escape potentials and use excess personnel and equipment.

This paper reports a study designed to describe and quantify the relative effect of institutional constraints and of managerial factors on prescribed burning costs in two Forest Service regions.

Methods

The data was collected, during 1986 summer, by a questionnaire. It was administered in person at several Ranger Districts within the Forest Service's Northern and Pacific Northwest Regions including portions of Idaho, Montana, Washington, and Oregon. The questionnaire was pretested by personnel at the Forest Service's Northern Region and improved both in content and in realism. Fire and fuel managers were exposed to prescribed burning scenarios typical of their Regions. A realistic burn plan was presented through written descriptions, aerial photographs, and on-site photographs of the area to be treated. Managers were asked to simulate the burn operating under strict guidelines for objectives outlined for them. Participants evaluated each plan under two burn objectives and three institutional constraints (Table 1). Possible burn objectives were site preparation for artificial regeneration and fuel load consumption for fire hazard reduction. The possible variations of the constraints were minimizing escape potential, complying with smoke emission standards, and minimizing burning cost.

Under each simulation of a burn plan, given the burn objectives and institutional constraints, participants documented the ignition technique(s) used, type of fireline constructed (hand or bulldozer), mopup classification, season and time of burn, and an estimate of equipment and personnel involved. Costs of each burn were estimated outside the interview. Costs were based on resources committed to the burn plan, execution, and mopup, and were calculated from a uniform set of unit costs in an engineering cost approach (González-Cabán et al. 1984).

Site variables were varied in alternative scenarios to test individual reaction to changes in the physical site characteristics of the four sites used in the study. This reaction was tested by changing physical variables, while maintaining the constraint to minimize fire escape. By analyzing the change in burn execution actions with varying physical site characteristics, everything else constant, manager responses that raise or lower fire cost could be isolated.

Twenty-four unique combinations of burn-plan objective, institutional constraints, and site characteristics were presented to surveyed individuals during the course of one day. Completion of the questionnaire took an average of 6 hours. The order of presentation of each scenario to an individual was noted to investigate possible biases due to fatigue. Individuals from the same area were presented with the questionnaires on the same day to minimize the possibility for preexisting knowledge of, and consultation about, the contents of the questionnaires. The order of presentation of the scenarios was randomized for each individual, but many participants reordered the scenarios to ease response.

Analysis of variance was used to examine the effects of managerial variables, burn-plan objectives, institutional constraints, and site characteristics on estimated burn costs. Managerial variables were represented by use of education, experience, and risk posture as crossed categories. Individuals were considered as nested within education-experience categories (Table 1). Burn-plan objectives, institutional constraints and site characteristics were treated as crossed factors within individuals. The time at which a given scenario was presented to a participant was assumed to have no effect on the distribution of estimated burn costs. The experiment consequently had a split-plot structure with whole plots corresponding to individuals and subplots corresponding to combinations of burn-plan objective, institutional constraints, and site characteristics.

Because no preliminary information was available, it was impossible to predetermine the desired sample size objectively. These preliminary results are based on information from 53 participants. Since completion of these participants' questionnaires, 63 new questionnaires have been collected and will be analyzed.

Since presentation of questionnaires was not replicated, some interactions must be assumed to be zero to obtain an estimate of error. Three-factor interactions involving "participant," and all four- and five-factor interactions were assumed to be zero on the general principle that high-order interactions tend to be smaller than lower-order interactions. The use of "education" and "experience" as factors in the data structure was hoped to account for much of the variability which would otherwise be attributed to interactions involving "participant." It was expected therefore that all interactions involving "participant" would be small. The assumption in particular that these higher-order interactions are zero seemed reasonable.

Table 1. Outline of Treatments Used in the Analysis of Variance

Treatment Factor	Factor Levels	
Education	High school A.A. degree Bachelor's degree or higher	
Experience	0-20 fires as burn boss 21-50 fires as burn boss 51+ fires as burn boss	
Institutional constraints	No escapes Comply with smoke	
emission standards	Minimize cost	
Burn-plan objectives	Fire hazard reduction Artificial regeneration	
Site characteristics	Site 1	15 acres 35 percent slope regular rectangle
	Site 2	23 acres 60 percent slope regular rectangle
	Site 3	75 acres 15-25 percent
slope		regular rectangle
	Site 4	17 acres 6-15 percent slope elongate rectangle

The analysis of variance procedure used was the Statistical Analysis System General Linear Models (GLM) (SAS Institute Inc. 1985). Construction of test statistics was determined using the algorithm given by Montgomery (1984), treating "participants" as a random factor and all other factors as fixed. Type III sums of squares were used for formation of test statistics. There were no missing treatment combinations. Some effects were further analyzed using Fisher's least significant difference (LSD) test.

Results

The ANOVA model used explained 94 percent of the total variation in total burn cost. Nine tested effects were found to be significant at a type I error rate of .05: the main effect of institutional constraint; the interaction of burn objective with experience; the main effect of site; the interaction of site and participant; and the interactions of institutional objective with experience, participant, site, site and education, and site and experience.

Fisher's least significant difference test was used to further investigate the effects of site, site within the minimization-of-escapes constraint, and institutional constraints. All pairwise comparisons of treatments within these groups exceeded the critical value of the test.

Sites 2, 3 and 4 each differed from site 1 primarily in one characteristic: site 2 differed primarily in slope, site 3 in size, and site 4 in shape (Table 1). The observed differences in cost estimates from these sites therefore indicate the cost effect attributable to these characteristics. The difference between site 1 and site 3 is the largest with respect to total estimated burn cost, estimated burn cost per acre, and total burn cost within the constraint that escapes should be minimized (Table 2). The increase in size imposed by site 3 therefore appears to have a larger effect than the changes in slope or shape imposed by sites 2 and 3.

Residual analysis was used to check the validity of the assumptions of ANOVA. Residuals were examined when plotted against predicted values and values of the classification variables. Residuals were also examined with respect to time of administration of the questionnaire. No obvious violations of the underlying assumptions of ANOVA were seen.

Discussion

The statistical significance of the main effect of institutional constraints indicates that, averaged across all factors considered here, prescribed burning costs changed with changes in the institutional constraints given to the burn bosses. The same statement can not be made with regard to burn objective. The two burn objectives presented in this study had little effect on burn expense. This finding is contrary to our expectations and should be investigated further to determine if this result is due to a lack of differentiation between the two burn objectives presented or to some other reason. Some written comments on the questionnaires implied that both objectives could have been achieved with the same burn.

A complex interplay of institutional constraints with both personal factors and site characteristics is highlighted by the significance of several interaction involving institutional constraints in conjunction with personal and site factors (Table 3). The appearance of the "institutional constraint-site" interaction indicates that survey participants treated a given site differently under different institutional constraints. The "institutional constraint-experience" interaction indicates that individuals with differing levels of experience reacted differently to changes in institutional constraints. Institutional constraints clearly are critical when planning a prescribed burning program because of their effect on managers' burn plans.

Total prescribed burning costs differed by institutional constraints for all sites (Table 2). Therefore, changes in institutional constraints likely would cause changes in prescribed burning costs. For example, in our study, changing the institutional constraint from "minimizing escapes" to "complying with smoke emission standards" caused an average cost reduction of $521, while changing the constraint from "minimizing escapes" to "minimizing cost" resulted in an average reduction of $1,856. Participants were told to carry out the simulated burns as if they were working in their present Forest Service environment, except that the given constraints were the overriding factor. So even when minimizing costs or complying with smoke emission standards, participants most likely tried to prevent any escapes. The central issue in our study was not cost estimation, however, but rather the fashion in which these estimates were affected by changes in managerial and institutional factors.

Ten model terms account for approximately 81 percent of variability in cost estimates (Table 3). The largest amount of variation (33 percent) is explained by the "participant" factor (which was used as an estimate of whole plot error), indicating that the individuality of each participant is the major factor explaining variability in burn costs. The "site-participant" interaction explains 21 percent of the variability and the "site" characteristics explains 16 percent. These

Table 2. Estimated prescribed burn costs by site.

Cost	Site				
	1	2	3	4	Fisher's LSD
	(dollars)	(dollars)	(dollars)	(dollars)	
Total cost per acre	227	177	100	151	*
Total burn cost	3400	4077	7523	2564	231
Cost Under constraint to mimimize escapes	4053	4849	8830	2989	400

*Because of unequal unit size, a single Fisher's LSD number cannot be presented. Sites 1, 2, and 4 and sites 3 and 4 are not separable.

Table 3. ercentage of ANOVA total sum of squares explained by selected factors (significant at a Type I error of .05) affecting prescribed burning cost estimates.

Effect	Percent
Participant*	33
Site-participant interaction	21
Site	16
Participant-institutional constraint interaction	6
Institutional constraint	2.7
Institutional constraint-experience interaction	1.0
Site-institutional constraint interaction	.6
Site-institutional constraint-experience interaction	.4
Site-institutional constraint-education interaction	.3
Burn objective-experience interaction	.1

* Participant was used as an estimate of whole plot error.

three factors (participant, site, and site-participant interaction) alone explain 70 percent of the total variation. The nine statistically significant effects (excluding participant) account for a little over 48 percent of the total variability.

Because the main effect of "site" was significant, site characteristics clearly should be an important factor in determining how a prescribed burn project is conducted. In multiple comparison tests, all possible pairwise comparisons of site exceeded the critical value. Size appears to have a larger effect on burn costs than does either change in slope or shape, which increases the amount of burn perimeter relative to the area burned.

Although burn costs were highest for site 3, on a cost-per-acre basis, the results show the existence of economies-of-scale mentioned by several authors (González-Cabán and McKetta 1986, Rich 1984, Wood 1988). The larger the unit burned, the lower its per acre cost (Table 2).

Summaries of total burn costs by participant's self-perceived risk posture reveals a contradiction between the way participants view themselves and their actual approach to the presented burn plans. For example, those that viewed themselves as risk averse had the lowest total cost of all. The risk neutral group (largest one) had the highest total cost, and the risk takers had intermediate costs (Figure 1).

This result can be explained in several possible ways. One is that participants did not understand our risk categories. Another more logical interpretation is that the way people react to risk in their personal life can be vastly different from the way they react in their working environment. Risk takers in their personal life may be more conservative in a working environment.

All participants in this study were trained within the same organization and the same standards and had absorbed the agency work behavior patterns. They had also, in many cases, seen the negative consequences of not complying with the standards, rules, or regulations established by the agency. This observation may have caused them to become conservative in their approach to prescribed burning.

Four of the five participants who described themselves as risk averse were clustered in the lowest experience category (0-20 burns as burn bosses). Their low burning cost estimates may suggest that they have not yet internalized the zero escape message of the agency, or they have not yet experienced any negative consequences because they have not yet "lost" any prescribed burn. Although they viewed themselves as risk averse, relative to more experienced persons, they appear to be acting more like risk takers at work. This whole area of how risk posture is linked to burn accomplishments and costs requires more research.

"Burn objective" was not a significant factor by itself. Total cost estimates for each site under each burn objective were, for all practical purposes, equal. Only the "burn objective-education" interaction included burn objective. This interaction was one of the smallest significant interactions in the ANOVA model, as measured by the percentage of the total variation explained (Table 3).

Some interesting results show up when looking at how managerial and professional factors, as measured through education and experience, affected prescribed burn costs estimates. Burn cost estimates varied by time-of-day and by experience for the most and least experienced of the participants (Figure 2). Those in experience category 2 did not seem to discriminate differences in burn costs by time-of-day at which burns are conducted. We cannot explain such behavior, especially when of the 17 participants in this category, 8 viewed themselves as risk neutral and 8 as risk takers.

The significance of ANOVA terms involving professional and managerial factors mean that these factors indeed have a direct relationship with the prescribed burn cost. This finding is congruent with our stated hypothesis.

Conclusions

These preliminary findings validate our stated hypothesis that institutional constraints directly affect the way prescribed burning bosses do their job, as reflected in their estimates of burn costs. One surprise result was that burn objective did not seem to significantly affect total prescribed burning costs. It was as if the interviewed participants had an "internal burn plan" in their mind which they used regardless of objective and location. Further analysis is needed to corroborate these preliminary findings.

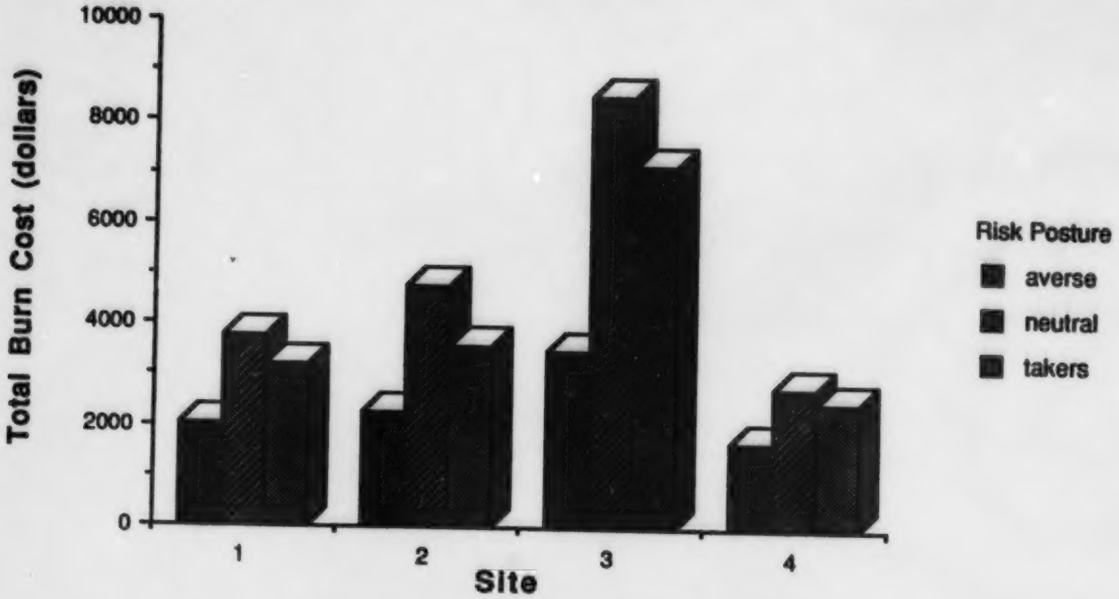


FIG 1. Total Burn Cost by Participant's Self-Perceived Risk Posture and Site.

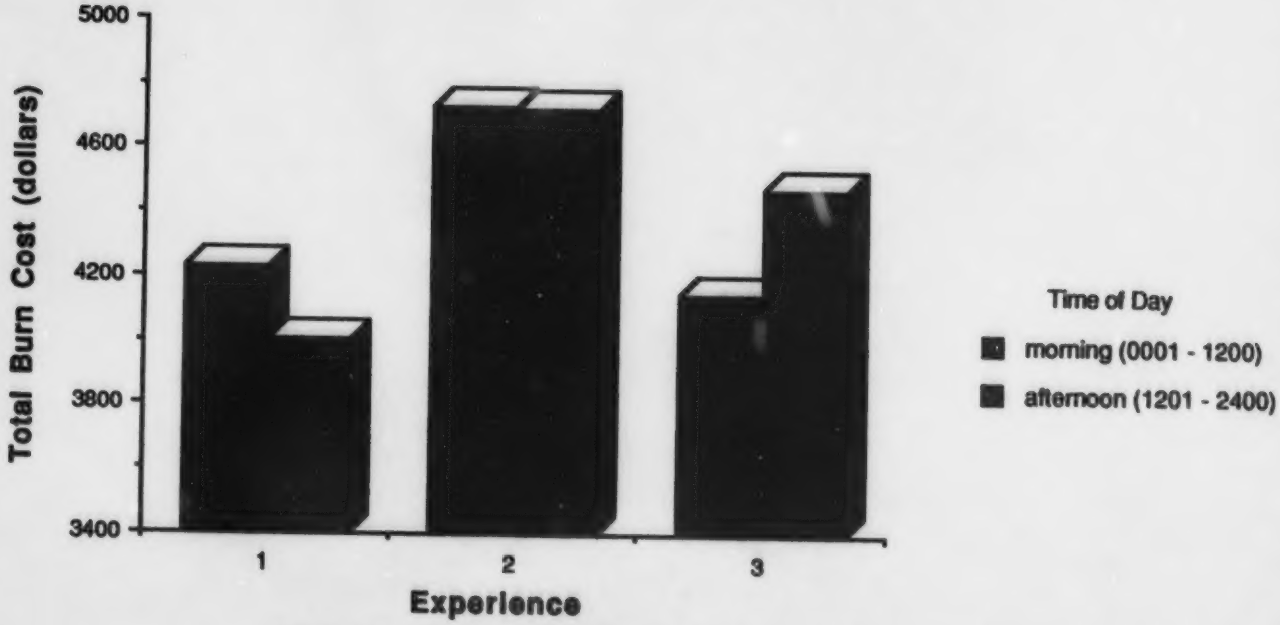


FIG 2. Total Burn Cost by Participant's Experience and Ignition Time. Experience categories are: 1 = 0 - 20 fires as burn boss, 2 = 21 - 50 fires as burn boss, and 3 = 50 + fires as burn boss.

References

BUNNELL, D. L. 1982. Post sale treatment cost analysis: a procedure for identifying planned prescribed fire costs. Missoula, MT: Lolo National Forest. Unpublished manuscript supplied by author.

GONZÁLEZ-CABÁN, A., C. W. MCKETTA, AND T. J. MILLS. 1984. Costs of fire suppression forces based on cost-aggregation approach. USDA For. Serv. Res. Paper PSW-171, Pac. Southwest For. and Range Exp. Sta.

GONZÁLEZ-CABÁN, A., AND C. W. MCKETTA. 1986. Analyzing fuel management cost. Western J. Appl. For. 1(4):116-121.

LOVELESS, R. S., JR., P. J. FLOWERS, D. H. JACKSON, AND E. G. SCHUSTER. 1982. Economic analysis of wildlife management costs in the Forest Service, Northern Region. Bull. 47. Missoula, MT: Mountain Forest and Conservation Experiment School, School of Forestry, University of Montana; 32 p.

MCKETTA, C. W., AND T. A. RICH. 1982 Preliminary findings: fuel management costs on the Lolo and Willamette National Forests. Unpublished manuscript supplied by author.

MONTGOMERY, D. C. 1984. Design and analysis of experiments. 2nd ed. John Wiley & Sons.

RICH, T. A. 1984. Prescribed burning cost: sources of variability on the Powell Ranger District Clearwater National Forest. Masters thesis. University of Idaho, Moscow, ID.

SAS Institute Inc. 1985. SAS User's Guide: Statistics, Version 5 Edition. Cary, NC: SAS Institute Inc.

WOOD, D. B. 1979. Fuel management opportunities on the Lolo National Forest: an economic analysis. USDA For. Serv. Res. Note INT-272. Intermountain For. and Range Exp. Sta.

WOOD, D. B. 1988. Costs of prescribed burning in southwestern ponderosa pine. Western J. Appl. For. 3(4):115-119.

Soil Nutrient and Pinyon Seedling Response to Fire Severity

M.G. HARRINGTON
Intermountain Research Station, Forest Service
U.S. Department of Agriculture
Missoula, Montana

Abstract

Mineral soil was collected from an 8-month-old pinyon-juniper (Pinus edulis Engelm. - Juniperus osteosperma [Torr.] Little) burn in northern Arizona and potted in a greenhouse for bioassays. Pinyon seeds were planted in mineral soils from four treatments: severe burn, light burn, unburned duff, and unburned interspace between trees. All treatments were watered equally and frequently to minimize moisture stress. The 4-month-old pinyon seedlings from the severely burned soils generally had smaller crowns and roots than those from other treatments. Soils from the light burn and unburned duff produced seedlings with the heaviest crowns and largest roots. Chemical soil analyses showed that the severely burned soils had significantly greater concentrations of nitrate-nitrogen, extractable phosphates, potassium, and calcium. Nutrient amounts in the lightly burned soils were generally equal to or greater than those in the unburned duff soils with interspace soils being the least fertile. The nitrate-nitrogen and extractable phosphates in the severely burned soils could have exceeded optimum levels possibly resulting in nutrient imbalances and thus reduced seedling growth. Implications are that piling and burning slash fuels on existing tree duff instead of broadcast or no burning could initially lead to zones of high nutrient availability but eventually could result in nutrient deficiencies.

Résumé

On a recueilli des sols minéraux dans un terrain brûlé il y a 8 mois, où il y avait des génévriers à pignons (Pinus edulis Engelm. - Juniperus osteosperma [Torr.] Little), du nord de l'Arizona. On les a mis dans des pots d'une serre pour effectuer des essais biologiques. On a planté des semences de pignon, dont on a surveillé la germination dans des sols minénalux de quatre traitements: gravements brûlés, des sols légèrement brûlés, d'humus non brûlés et des sols d'intervalles non brûlés séparant les arbres. On a arrosé tous les traitements d'une façon identique, assez souvent pour éviter le manque d'humidité. Les plants des pignons de 4 mois provenant des sols gravement brûlés possédaient généralement des couronnes et des racines plus petites que les plants des autres traitements. Les sols provenant des emplacements légèrement brûlés et d'humus non brûlés ont produit des plants dotés des couronnes les plus fournies et des racines les plus longues. L'analyse chimique des sols indique que les sols gravement brûlés possédaient des concentrations nettement supérieures de nitrate-azote disponible, de phosphate, de potassium et de calcium susceptibles d'extraction. La quantité des éléments nutritifs des sols légèrement brûlés était généralement égale ou supérieure à celle des sols d'humus, les sols des intervalles étant les moins fertiles. Les concentrations de nitrate-azote et de phosphates des sols gravement brûlés auraient pu atteindre des niveaux dépassant l'optimum, pouvant résulter à un déséquilibre d'éléments nutritifs d'où la croissance réduite des plants. Il s'ensuit qu'en brûlant les combustibles après les avoir rassemblés en tas sur l'humus des arbres au lieu de les brûler quand ils sont régulièrement répandus ou aucun brûlage, on risque de créer des zones à forte concentration d'éléments nutritifs et éventuellement des zones manquant de ces éléments.

Introduction

Pinyon-juniper woodlands occupy about 19 million ha in the Western United States (Evans 1988). Much of the southwestern woodlands was previously managed primarily for range production with emphasis on elimination of tree species (Springfield 1976). More recently, the value of pinyon (Pinus edulis Engelm.) and juniper (Juniperus osteosperma [Torr.] Little) fuelwood has increased, adding to management complexity. Following both range improvement and fuelwood harvesting operations, prescribed fire is commonly used to dispose of tree debris for hazard abatement, to stimulate suppressed forage species, to improve accessibility to animals, and to improve aesthetics. Debris is frequently piled for easy ignition and for more complete consumption. Many of the key nutrients in these woodlands are concentrated under pinyon and juniper trees because of vertical and horizontal translocation to the trees and decomposition of tree litter (Barth 1980, Everett et al. 1986). This pattern makes the nutrient capital vulnerable to intensive management practices (Debano and Klopatek 1987). The objectives of this study were to compare soil nutrient concentrations from four field microsites following pinyon-juniper slash and tree burning and to

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

observe pinyon seedling greenhouse growth in response to soil nutrient differences of various burn treatments.

Methods

A 275-ha pinyon-juniper prescribed burn was conducted by the U.S. Forest Service in August 1985 in northern Arizona, 12 km south of Grand Canyon National Park. The primary burn objectives were to reduce pinyon-juniper invasion, rejuvenate decadent cliffrose (Cowania mexicana D. Don), and reduce 20-year-old slash piles. Weather during effective burning included temperatures from 22° to 30°C, relative humidities between 15 and 20%, and winds between 4.5 and 6.5 m/s. Strip head fires were used to generate runs up to 270 m. Dead fuel moisture averaged 5% and live tree foliar moisture averaged 115%.

In April 1986, mineral soil was collected from four contrasting microsites within the burned area. The treatments were: (1) severely burned soils (SB) over which an undetermined amount of piled slash burned and consumed most of the pinyon duff, (2) lightly burned soils (LB) over which no slash was burned and pinyon duff was only partially consumed, (3) unburned duff soils (UD) that were under the duff of a living pinyon with no burning, and (4) unburned interspace soils (UI) that were between trees where little organic matter existed. Soils were collected at six sites from each of the four treatments. Where remaining, the organic layers were scraped away and only mineral soil was taken. Soils were sampled in 5-cm layers from 0 to 15 cm deep, and each layer from each microsite was placed in a separate plastic bag.

The soils were brought to a greenhouse, passed through a 2-mm soil sieve, and potted by original depth into 17-cm high by 15-cm wide plastic pots. The 24 pots (4 treatments x 6 replications) were randomly arranged in the greenhouse and planted with 25 pinyon seeds collected in 1985 near the burned site.

Before and during seedling emergence, the pots were watered twice weekly. After about a month, when emergence was complete, all but three seedlings were clipped from each pot. Watering was reduced to once a week, which was considered sufficient to minimize moisture stress. The location of all pots within the greenhouse was randomly changed weekly. Diurnal conditions in the greenhouse averaged 18° to 30°C and from 40 to 80% relative humidity.

When the seedlings were about 4 months old, they were removed from the pots by shaking the roots free of soil. Shoot and root lengths were measured, all roots longer than 1 cm were counted, and shoot and root dry weights were determined after oven drying at 70°C for 24 hr.

A small soil core was extracted from each pot when seedlings were 1 month old and at the end of the experiment. The soils were kept separate by depth (0 to 5 cm, 5 to 10 cm, and 10 to 15 cm) and extracted in 2N KCl solution. Ammonium- and nitrate-nitrogen were determined colorimetrically using an autoanalyzer. Because ammonium-nitrogen concentrations averaged less than 5% of nitrate-nitrogen, the former will not be reported.

At the end of the experiment, additional soil chemical properties were determined for each 5-cm depth increment in each pot. Soil pH was determined using a pH electrode in a 1:1 soil:water paste. Soil organic matter was determined by loss-on-ignition at 430°C (Davis 1974). Phosphates were extracted with 0.5 N $NaHCO_3$; potassium, calcium, and magnesium were extracted with 1N NH_4OAc after Page et al. (1982); and all were measured colorimetrically.

Seedling characteristics were analyzed using analysis of variance, nested design, followed by Duncan's multiple range test to determine treatment mean differences. A completely random design of analysis of variance was used to analyze for soil nutrient differences. Treatment differences were also compared using Duncan's multiple range test.

Results and Discussion

Pinyon seedlings growing in the SB soils were generally smaller than those in at least two of the other treatments. Seedlings in the LB soils were generally the largest but were significantly different than those grown in one or both of the unburned soils only in shoot weight and total lateral root length (Table 1). Available soil moisture, insolation, and soil temperature are factors that can greatly differ in field microsites where the four treatment soils were collected. Differences in these components among microsites would likely result in pinyon seedling growth differences in the field (Harrington 1987). However, because all pots were watered similarly and the temperatures, relative humidities, and insolation were equal among treatments, seedling size differences should have resulted primarily from chemical and, perhaps, physical dissimilarities in the soil.

Table 1. Characteristics of 4-month-old pinyon seedlings grown in four treatment soils.

Treatment soils	Shoot weight	Root weight	Crown length	Taproot length	Total lateral root length	Ave. lateral root numbers
	- - - - mg - -		- - - - - - - - cm - - - - - - - -			
LB	24.3a[1]	15.1a	5.3a	46.2b	80.0a	20.2a
UD	22.1ab	15.3a	5.4a	56.8a	49.8b	18.4a
UI	19.5bc	13.4a	4.8a	52.8ab	53.2b	18.7a
SB	17.9c	12.9a	3.8b	29.7c	37.3b	10.9b

[1] Means in columns with different letters are significantly different at the $P < 0.10$ level.

High organic matter in the UD and LB soils was a result of their field position under deep pinyon litter and duff and its incorporation thereof (Table 2).

Greater organic matter in the mineral soil under pinyon and juniper canopies has also been reported by Barth (1980) and Klopatek (1987). Organic matter in the SB soils was likely equal to the others prior to burning.

Table 2. Percent organic matter in three depths of four treatment soils.

Treatment Soils	Soil Depths 0-5 cm	Soil Depths 5-10 cm	Soil Depths 10-15 cm
UD	9.5a[1]	8.2a	7.5a
LB	9.3a	8.1a	6.6b
SB	6.4b	5.9b	6.1b
UI	5.5b	5.5b	5.4c

[1] Means in columns with different letters are significantly different at the $P < 0.10$ level.

Organic matter as a source of mineral nutrition depends upon decomposition rates. Therefore, sites with large amounts of organics and inhibited decomposition may have stagnant nutrient cycling. Conversely, sites that experience rapid decomposition rates will have a flush of available nutrients that will eventually become limited if organic matter is minimal. Generally, fires that consume substantial amounts of organics create site conditions favorable to rapid decomposition rates (Woodmansee and Wallach 1981).

In addition to being a primary source of mineral nutrition given active decomposition, organic matter can also improve moisture-holding capacity and reduce bulk density of mineral soil (Brady 1984). Lower bulk density can lead to more rapid root penetration. However, the soil with the most organic matter (UD) did not have seedlings with the greatest total lateral root length (Table 1), either because lower bulk densities did not result from greater organic matter or factors other than physical effects were more influential for seedling growth.

Large differences in availability of soil nitrogen were measured among treatments when pinyon seedlings were 1 month old (July) and again 3 months later (October). SB soils had significantly higher concentrations of nitrate-nitrogen than the other treatments at all depths, except the LB surface layer (Table 3). Nitrogen availability in the UI soils was consistently the least. Nitrates decreased from the surface layers down in all treatments except the July SB sample in which the highest concentration was in the 10 to 15 cm layer. This could have been due to leaching of high concentrations of mineral nitrogen from the surface layers that were a direct oxidation product of burning of large quantities of organic matter. The amounts of nitrate-nitrogen in the two unburned soils were also greater than reported by Debano et al. (1987) and Klopatek (1987) for similar depths in juniper and pinyon soils in Arizona under field conditions.

Table 3. Concentrations (mg/kg) of nitrate-nitrogen from three depths of four treatment soils.

Treatment soils	Soil depths 0-5 cm July	0-5 cm Oct.	5-10 cm July	5-10 cm Oct.	10-15 cm July	10-15 cm Oct.
SB	68a[1]*	193a	82a	80a	121a	101a
LB	66a*	162ab	26b	37b	29b	30b
UD	42a*	98bc	18b	26bc	19b	20bc
UI	14b*	45c	6b	11c	7c*	15c

[1] Means in columns with different letters are significantly different at the $P < 0.10$ level.

*Indicates July mean is significantly different from October mean at the $P < 0.10$ level.

All treatments showed a two- to three-fold increase in surface nitrate-nitrogen from July to October. Any increase in nitrates due to leaching or mineralization below 5 cm was likely offset by seedling absorption as concentrations within the rooting zone changed minimally from July to October. The largest percentage and only significant increase in subsurface nitrates took place in the UI soil, which had the lowest initial concentrations.

Although the amounts of nitrate-nitrogen in the two unburned soils were greater than reported by Debano et al. (1987) and Klopatek (1987) for juniper and pinyon soils under field conditions, Klopatek (1987) found that nitrate accumulations in pinyon soils incubated for 60 days were at least equal to those reported in Table 3 for unburned soils. It should be noted that the conditions of adequate moisture availability under which this study was conducted certainly lead to greater nitrification than under field conditions. However, Table 3 does not represent the results of potential nitrification of each soil because temperature, aeration, and light were not controlled as is commonly done in laboratory nitrification studies (e.g., Powers 1980).

Extractable phosphates were also greatly elevated by burning, and concentrations increased with severity of burning (Table 4). A consistent decrease of 40 to 60% occurred in each treatment from the upper 5 cm to the lower 5 cm. The unburned soils contained two to four times the phosphates found by Gifford (1981) and Debano et al. (1987) for pinyon and juniper soils under field conditions. In a simulated burn experiment, Debano and Klopatek (1988) found up to a two-fold increase in extractable phosphates of the upper 5 cm of mineral soil. Concentrations approached 135 mg/kg, which is slightly less than the 157 mg/kg found in the LB soils but about half of that found in the SB soils (Table 4). However, Debano and Klopatek (1988) reported extractable phosphate concentrations in the residual litter ash and duff following a dry soil burn to exceed 300 mg/kg immediately after the simulated burn. Duff phosphates decreased with time whereas ash phosphates did not.

Table 4. Concentrations (mg/kg) of extractable phosphates in three depths of four treatment soils.

	Soil depths		
Treatment soils	0-5 cm	5-10 cm	10-15 cm
SB	243a[1]	174a	123a
LB	157b	119b	63b
UD	52c	46c	32c
UI	39c	28c	22c

[1]Means in column with different letters are significantly different at the $P < 0.10$ level.

In the current study, it is not known if phosphates had increased or decreased because only one sample was collected. However, because the values in the burned soils were exceptionally high, the assumption might at least be made that concentrations were decreasing minimally. Much ash was incorporated in the surface of the SB soils, so extractable phosphates could have remained high, as Debano and Klopatek (1988) found for pinyon ash, as long as the ash remained on site. Mineralization could have also helped keep concentrations high in the surface layers, but the phosphorus mineralization processes are complex (McGill and Cole 1981). This is in contrast to Debano and Klopatek (1988) who indicated an immediate postburn increase in extractable phosphates followed by a rapid decline, approaching unburned levels in 45 days. Differences in degree of thermal degradation of organic matter between their low severity simulated burn and the high severity of an actual slash burn reported here could explain the contrasting phosphate concentrations. Leaching could have contributed to the elevated phosphates in the lower depths, but phosphate is not highly mobile (Paul and Clark 1989). Phosphate containing ash likely sifted into lower depths with frost heaving, a regular winter event.

Soil pH was increased slightly as a result of burning, with the most severe burn causing the greatest increase (Table 5). Difference in pH of 0.2 to 0.4 would normally result in minor dissimilarities in nutrient availability, primarily for phosphorus, given equal quantities and forms of these nutrients (Brady 1984). However, since quantities of most nutrients varied greatly among treatments, pH differences of this magnitude likely had little influence on nutrient availability.

Of the three cations measured, potassium and calcium showed distinct increases with burning (Table 5). However, burned soils showed an unexpected magnesium reduction. Debano et al. (1987) noted increases in mineral soil potassium with the burning of juniper debris but no change in calcium or magnesium.

Table 5. Average levels of pH, potassium, calcium, and magnesium at 0 to 15 cm depths in four treatment soils.

Treatment Soils	pH	Potassium	Calcium	Magnesium
		- - - - - - - - - meq/100g	- - - - - - - - -	
SB	7.8a[1]	1.7a	27.7a	2.7a
LB	7.6ab	1.5a	20.2b	2.8a
UD	7.4b	1.2b	16.9c	4.0b
UI	7.4b	0.8c	13.9c	4.1b

[1]Means in columns with different letters are significantly different at the $P < 0.10$ level.

Gifford (1981) reported significant potassium increases following pinyon slash burning that were still apparent 1 year after burning. Because an increase in cations would normally be expected in organic matter ash, the magnesium decrease could have been caused by abnormally high absorption by pinyon seedlings to complement possible luxury consumption of available nitrogen and phosphorus. An alternative explanation is that an initial increase in magnesium availability in the ash led to rapid leaching.

Conclusions

Debano and Klopatek (1987) pointed out the vulnerability of the pinyon-juniper nutrient capital to intensive management including harvesting, grazing, and prescribed burning. Because of high nutrient concentrations in the litter and duff microsites under tree canopies, any disturbance to these areas could result in substantial, long-term nutrient losses due to volatization, rapid mineralization, leaching, and immobilization.

Pinyon-juniper debris burning is common following fuelwood harvesting or rangeland conversion operations for hazard reduction, forage stimulation, and aesthetics. For more efficient and complete fuel consumption, piles are often created on or near duff deposition sites, where above ground site nutrients are concentrated. Pinyon and juniper duff burns slowly and incompletely by itself but can be completely consumed if covered by a long-burning pile of tree tops and large branches.

This study indicates that concentrations of extractable nitrogen and phosphorus can be dramatically elevated in the mineral soil for up to a year following severe burning. These increases are likely due to initial mineralization of the organic matter by fire, possibly followed by rapid microbial mineralization on the thermally degraded residual organics. Results suggest that one or more nutrients could have been in high enough concentrations in the severely burned soils to reduce pinyon seedling growth. The nature of the detriment could have taken one of at least three forms: levels of one or more nutrients directly toxic to plants, high levels of many nutrients creating a concentrated soil salt solution, or, most likely, high plant usage of one or more nutrients leading to a deficiency of a less available nutrient.

The importance of this result is not that plants under field conditions will be impacted by toxic levels of nutrients. In fact, the postburn mineralization rates were likely higher in the greenhouse without moisture deficits than under field conditions. But mineralization will be greater on severely burned sites than unburned sites in the field and will take place where scant organic matter remains. Thus, as available forms of nutrients are released, most could be lost by leaching and chemical or microbial immobilization. Nutrient replacement would be slow because the dry climate precludes rapid recovery of vegetation, organic inputs, and nutrient cycling. Implications are that severe burning due to slash piling and high organic matter consumption should be avoided on pinyon-juniper sites that have zones of concentrated organics and nutrients.

References

BARTH, R.C. 1980. Influence of pinyon trees on soil chemical and physical properties. Soil Sci. Soc. Am. J. 44:804-809.

BRADY, N.C. 1984. The nature and properties of soils. MacMillan Publishing Co., New York.

DAVIS, B.E. 1974. Loss-on-ignition as an estimate of soil organic matter. Proc. Soil Sci. Soc. Am. J. 38:150-151.

DeBANO, L.F., and J.M. KLOPATEK. 1987. Effect of management on nutrient dynamics in southwestern pinyon-juniper woodlands. P. 157-160 In Management of subalpine forests: Building on 50 years of research. Symposium Proceedings, July 1987, USDA For. Serv. Gen. Tech. Rep. RM-149. Intermt. Res. Sta.

DeBANO, L.F., and J.M. KLOPATEK. 1988. Phosphorus dynamics of pinyon-juniper soils following simulated burning. Soil Sci. Soc. Am. J. 52:271-277.

DeBANO, L.F., H.M. PERRY, and S.T. OVERLY. 1987. Effects of fuelwood harvesting and slash burning on biomass and nutrient relationships in a pinyon-juniper stand. P. 382-386 In Pinyon-juniper conference. Symposium Proceedings, Jan. 1986, USDA For. Serv. Gen. Tech. Rep. INT-215. Intermt. Res. Sta.

EVANS, R.A. 1988. Management of pinyon-juniper woodlands. USDA For. Serv. Gen. Tech. Rep. INT-249. Intermt. Res. Sta.

EVERETT, R.L., S.H. SHARROW, and D. THRAN. 1986. Soil nutrient distribution under and adjacent to singleleaf pinyon crowns. Soil Sci. Soc. Am. J. 50:788-792.

GIFFORD, G.F. 1981. Impact of burning pinyon- juniper debris on select soil properties. J. Range Manage. 34:357-359.

HARRINGTON, M.G. 1987. Characteristics of 1-year-old natural pinyon seedlings. USDA For. Serv. Res. Note RM-477. Rocky Mt. Sta.

KLOPATEK, J.M. 1987. Nitrogen mineralization and nitrification in mineral soils of pinyon-juniper ecosystems. Soil Sci. Soc. Am. J. 51:453-457.

MCGILL, W.B., and C.V. COLE. 1981. Comparative aspects of cycling of organic C, N, S, and P through soil organic matter. Geoderma 26:267-286.

PAGE, A. L., R.H. MILLER, and D.R. KEENEY. eds. 1982. Methods of soil analysis, Part 2: Chemical and microbiological properties. Agronomy. 9:159-161, 421-422.

PAUL, E.A., and F.E. CLARK. 1989. Soil microbiology and biochemistry. Academic Press, San Diego.

POWERS, R.F. 1980. Mineralizable soil nitrogen as an index of nitrogen availability to forest trees. Soil Sci. Am. J. 44:1314-1320.

SPRINGFIELD, H.W. 1976. Characteristics and management of southwestern pinyon-juniper ranges: the status of our knowledge. USDA For. Serv. Res. Pap. RM-160. Rocky Mt. Sta.

WOODMANSEE, R.G., and L.S. WALLACH. 1981. Effects of fire regimes on biogeochemical cycles. Ecol. Bull. 33:649-669.

Modeling the Downward Heat Pulse From Fire in Soils and in Plant Tissue

R.D. HUNGERFORD
Intermountain Research Station, Forest Service
U.S. Department of Agriculture
Missoula, Montana

Abstract

Many of the first-order fire effects on soils and plant communities are a function of the degree of heating of the soil and organic layers by the fire. Fire severity and fire intensity have been used to describe fire effects, but attempts at relating these parameters to the downward heat pulse in the soils have been unsuccessful. There is no direct correlation between fire intensity and heat pulse in the soil. This paper presents a conceptual model of soil heating in response to fire. The modeling approach describes heat transfer from the fire to the soil surface, heat transfer through the soil, and heat transfer into biota in the soil medium. Existing modeling approaches are reviewed and processes of heat transfer are discussed. Review of the processes and modeling efforts suggest that more research is needed on heat transfer by vapor flow in the soils.

Résumé

Bon nombre des effets premiers du feu sur le sol et les communautés végétales sont fonction du degré de chauffage du sol et des couches organiques par le feu. Les effets du feu ont souvent été décrits par la gravité et l'intensité d'un incendie, mais les tentatives en vue de corréler ces paramètres avec la prepagation vers le bas de la chaleur dans les sols ont été vaines. Il n'existe aucune corrélation directe entre l'intensité d'un incendie et la propagation de la chaleur dans le sol. Le présent article fera état d'un modèle théorique destiné à prédire le degré de chauffage du sol à la suite d'un incendie. L'approche de modélisation décrit la transmission de la chaleur d'un incendie à la surface du sol, la transmission de la chaleur au travers du sol et la transmission de la chaleur à l'intérieur de la biote dans le sol. Les approches de modélisation qui existent sont revisées et les processus de transmission de la chaleur sont discutées. Une revue des processus et des efforts de modélistion indique qu'il faudra effectuer d'autres recherches sur le déplacement de la vapeur, dans le sol.

Introduction

Quantitative predictions of downward heat flow from fires into the soil and into soil biological components are needed to assess fire effects. Reliable methods of evaluating management alternatives are lacking because relationships between biological responses, preburn conditions, and fire characteristics are not available. Existing methods are empirical and site specific. Explanatory models that represent ecological and physiological processes and permit more generalizable predictions are needed.

The objective of this paper is to review past work on soil heating under fires by reviewing some of the modeling approaches and to present a conceptual model of downward heat pulse from fire through the soil and into biological systems. Development of the conceptual model draws on previous modeling efforts, on heat transfer theory, and observations of temperature profiles under actual fires.

Research modeling of soil heating has been limited. Measures of fire intensity and other fire characteristics do not seem to influence the downward heat pulse into the soil (Rowe 1983, Shearer 1975, Brown et al. 1985). Researchers who have developed quantitative models based on principles of heat transfer have dealt only with part of the system or they have not studied fire as the heat source.

A biological index of soil heating is needed that can relate the effects of a fire directly to biological systems in the soil (plants, animals, microorganisms).

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

This index can be used to evaluate alternative management opportunites. Some succession models that predict vegetation response following fire use some measure of fire intensity or severity as input (Morgan and Neuenschwander 1985, Keane 1987, Moeur 1985, Hungerford 1987). Most of these succession models use a fire severity rating, which is qualitatively related to soil heating by depth of char (Ryan and Noste 1985) and depth of burn (Rowe 1983) or measures of fire intensity. The prediction capability of these models could be improved if we had a method of predicting soil temperature profiles. Heat flows from the fire are important, but we don't know how to directly interpret the effects.

Previous Modeling Approaches

In the 1930's, silviculturists using prescribed burning expressed concern about fire effects on organic matter losses, changes in soil structure, productivity, losses of nutrients, etc. Initially, investigators measured soil temperatures for different types of fires (Heyward 1938, Beadle 1940, Sampson 1944). Later, workers used visual characteristics to classify fire severity and related these to temperature profiles (Tarrant 1956, Bentley and Fenner 1958). Other investigators developed some empirical relationships to predict soil temperature profiles (Shearer 1976, DeBano et al. 1979). Quantitative models have also been attempted using theoretical heat transfer algorithms (Scotter 1970, Aston and Gill 1976).

The goal is to develop mathematical models that describe functional flow of mass and energy and to eliminate restrictive empirical methods (Bristow et al. 1986). Models based on physical principles, which describe the underlying causes, have less need for calibration and are generally more widely applicable. Heat transfer theory has been used to model heat and moisture transfer in biological systems for a number of years. Soil physicists have developed a variety of models to predict heat flow in soils. A considerable number of these models were aimed at understanding the physics of heat and moisture transfer in soils (DeVries 1958, Wierenga and DeWitt 1970, Hanks et al. 1971, Bristow et al. 1986). Other models were developed to predict effects of soil environment changes on biological systems (DeVries and Afgan 1975, Stathers et al. 1985). None of these models have been applied to situations with elevated temperatures (above 100°C) that would represent fire conditions.

The first realistic attempt to model heat transfer and temperatures in the soil beneath fires was made by Scotter (1970), but the effects of soil moisture changes were not evaluated. Since then only a few attempts have been made to model the downward heat pulse in soil beneath fires (Aston and Gill 1976, Chinanzvavana et al. 1986, Pafford et al. 1985, El-Doma et al. 1984).

Conceptual Model

We are attempting to develop a downward heat flow model with three components: (1) the fire as the source of heat, (2) the soil as the medium that transmits the heat, and (3) the plant parts or other organisms that absorb or receive the heat (Fig. 1). To model and predict fire effects, all three components need to be mathematically linked.

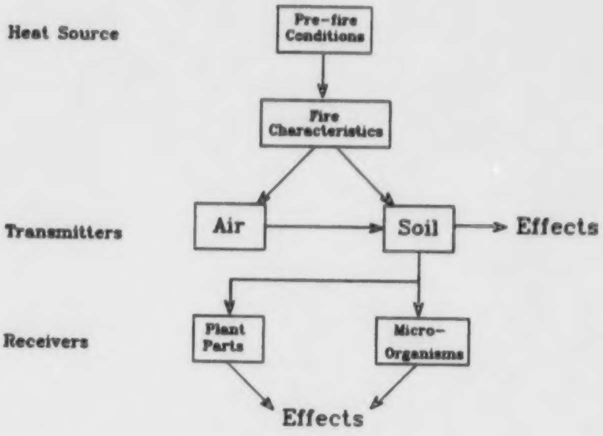


FIG 1. Components of the system to describe the downward heat flow from a fire. Elements of the system are identified as being part of the heat source, transmitters of the heat or receivers of heat.

A more detailed diagram of the system components is shown in Figure 2. The state variables and the processes are identified for modeling heat flow through the fire-soil-biota system. The diagram illustrates pathways for heat from surface and ground fires where duff can be a heat source or a transmitter. The amount and rate of heat generated is described by the fuel characteristics and by environmental conditions. The transmitters of heat are the atmosphere, the soil, gases generated during the combustion process, and moisture. The receivers of interest in the soil system are the soil components and plant and animal life in the soil system (roots, insects, fungi, bacteria, mychorrizae, etc.).

The conceptual model (Fig. 2) describes flow of heat through the system showing the processes that control flow between system components. The major decision is whether duff is present or not. Modeling heat transfer is different and more complicated if duff is present. Duff acts as an insulator to movement of heat if it does not burn. If it burns, it is an important additional source of heat because it significantly increases the duration of burning. The processes and the factors affecting the transfer of heat through the system (Fig. 2) will be discussed in more detail in the following sections.

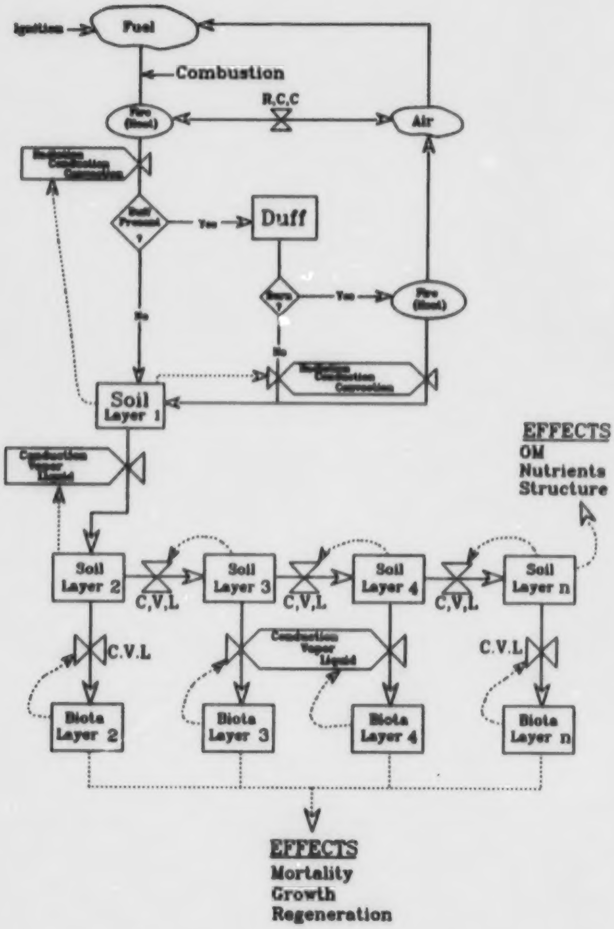


FIG 2. Conceptual model diagram of downward heat pulse from a fire into the soil and biological systems. Rectangular boxes represent state variables and solid lines between the boxes represent heat flow between the state variables. The processes that control the amount of heat between the state variables are shown by the "bow ties" on the lines between the boxes. Information from the state variables (represented by dotted lines) influences the processes and rates of heat flow.

MODELING HEAT FROM FIRE TO SOIL

A major problem with predicting soil heating is our inability to quantitatively relate pre-fire conditions and fire characteristics to the downward heat pulse. Wells et al. (1979) discussed proposed correlative parameters and concluded that eventually a purely physical model describing downward heat flux to the litter and soil must be formulated. Rowe (1983) noted that release of energy as the fire passes may bear little relation to survival of plant parts buried in the soil. Shearer (1975) also showed that fire intensity alone was not closely related to soil heating and root mortality. Moisture content of the duff and soil and duration of the fire were also important. Ryan and Noste (1985) also state that factors other than fire intensity determine the downward heat pulse. Albini's (1975) attempt to relate fire intensity to duff burnout and soil heating and to develop a theory of duff burnout was not successful. The lack of success was largely due to the variability of the burns, measurement problems, and the complexity of the heat transfer processes.

A major difficulty of modeling heat flow from a fire to the soil is the complexity of describing the heat transfer across the boundary layer between the fire and the underlying surface. In Figure 2, the fuel has a certain heat content or the potential to release a given amount of energy upon burning. After ignition the fire releases a given amount of heat at some rate. The combustion process is included for completeness, but the details are not discussed. The important point is that some heat is released. The heat generated by the fire is transferred to unburned fuels raising their temperature to ignition, to the atmosphere (air in the diagram), and to the soil or litter surface.

The heat is transferred by radiation, convection, and conduction. Convection and radiation dominate. Conduction is important within a fuel element and between elements in contact. Convection is probably the dominant process for heat transfer over radiation. Several investigators found only about 8% of the heat energy released in burning is absorbed and transmitted downward to the soil or litter (Packham 1969, DeBano et al. 1977, Raison et al. 1986). The rest of the heat is lost to the atmosphere or to unburned fuels. We know little about the proportion of the heat transferred by the three process in a forest fire. Chandler et al. (1983) indicate that the ratio of convective to radiant heat is 3 to 1 for a small fire in pine litter and is 9 to 1 for a large stationary fire in pine slash. However, they also considered radiation to be the dominant heat transfer mechanism. Convection was neglected in a model proposed for ground surface heating by Pafford et al. (1985). Chinanzvavana et al. (1986) used an empirical approach in an analysis of heat transfer beneath burning straw because of the inherent complexity of energy transfer between the fire and the soil surface layer.

Heat from the surface fire impinges on mineral soil or litter or duff first. If duff is present it may or may not ignite. If duff is not consummed, it insulates the mineral soil significantly reducing heat flow into the soil. If the organic layers burn by smoldering combustion, additional heat is available to mineral soil for longer periods. Heat is transferred through the duff into the soil by radiation, convection, and conduction. Whether or not the duff burns, conduction plays a much larger role in transferring heat. Thus, some of the heat transfer parameters will have different values than when duff is absent.

A number of variables influence the total heat generated and heat flux between a fire and the soil surface layer or the organic layer above the soil surface (Fig. 3). Fuel load, fuel moisture, environmental conditions such as temperature, wind, and relative humidity along with other variables influence the heat output and rate of burning. The heat output of the fire and the resultant temperature influence the processes of heat transfer discussed above. Absorption of the heat by the surface below the fire is dependent upon the surface characteristics and the underlying material (Fig. 3). Emissivity of the surface, distance from the surface to the heat source, temperature of the surface, and temperature of the heat source determine the radiative heat flux. Thermal conductivity and heat capacity of the surface layer determine the ability of the organics or mineral soil to move heat away from the surface to lower layers, thus influencing the heat flux through the surface. Moisture content of the layer has a considerable influence on thermal conductivity and heat capacity. Reduced heat flux through the surface layer and lower layers will result in more heat lost from the surface to the air or objects above the surface through radiation and convection.

The literature clearly shows that fundamental analysis is extremely complicated. The fact that so many processes are involved in this boundary between the combustion zone and the surface, and that so much variation exists, has caused most to avoid the problem or to attempt empirical solutions. A useful empirical approach may be that used by Chinanzvavana et al. (1986), calculating heat flux at the surface as a fraction of the total energy released in burning divided by the expected burning time.

MODELING HEAT TRANSFER WITHIN THE SOIL

Once the heat has reached the mineral soil surface and a flux has been established through the surface layer, heat is transferred in the soil by conduction, diffusion of water vapor, and mass flow of water (Fig. 2). Conduction is generally considered to be the dominant process of heat transfer in soils, but transport of heat by vapor flux can account for up to 60% of the total heat transfer in some cases (Westcot and Wierenga 1974). The contribution of heat transfer by liquid flux is probably small (10% or less), but this needs to be evaluated. Many assumptions made in modeling heat flow in soils for normal seasonal and diurnal temperature fluctuations are invalid for the temperature gradients such as those encountered under fires. As a result, traditional diffusion type equations that adequately describe heat flow in dry soils are invalid because of convection and gaseous exchange phenomena (DeBano et al. 1977).

Some common approaches to modeling heat transfer through the soil consist of dividing the soil into layers and using numerical solutions for difference equations to calculate heat and moisture fluxes across each layer (Bristow et al. 1986, Westcot and Wierenga 1974, Aston and Gill 1976). Heat and water contents of each layer are updated for each time step as a consequence of temperature gradient changes, and evaporation or condensation. Temperature for each layer at each time step can then be calculated. Heat flow by conduction is dependent upon the temperature gradient, thermal conductivity, and heat capacity (Fig. 4). Because thermal conductivity and heat capacity vary as a function of moisture content, moisture flux calculations must be coupled with the heat flux calculations. Updated moisture contents are needed to calculate thermal conductivity and heat capacity for each time step. Heat transfer by vapor flow (Fig. 4) is determined by the temperature gradient, porosity of the soil, partial pressure of water vapor in the soil, the diffusion coefficient, the latent heat of vaporization for water, and some other coefficients (Westcot and Wierenga 1974). Heat transfer by liquid flow is determined by

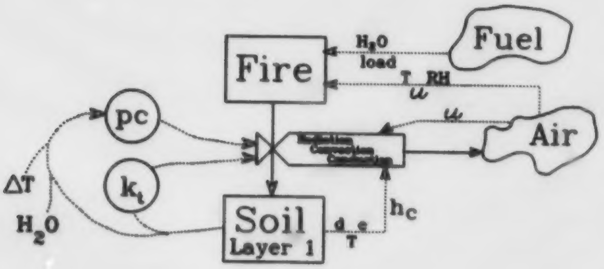


FIG 3. Details of the transfer of heat for the fire to soil layer 1. Sources and sinks of heat are shown by the irregular shaped boxes. The driving variables that influence the heat transfer process are along the dotted lines. Driving variables in the circles are calculated variables. Key to the symbols: pc = heat capacity; k_t = thermal conductivity; H_2O = moisture content; load = fuel loading; T = temperature gradient; RH = relative humidity; u = wind velocity; d = distance between the heat source and the soil surface; e = emissivity of the soil surface; h_c = convective coefficient.

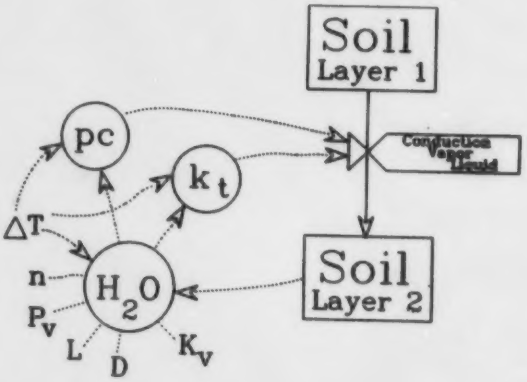


FIG 4. Details of the transfer of heat within the soil layers. The driving variables that influence the heat transfer processes are along the dotted lines. The circles represent calculated driving variables. Key to the symbols: pc = heat capacity; k_t = thermal conductivity; H_2O = moisture content; T = temperature gradient; n = enhancement factor; P_v = vapor density; L = latent heat of vaporization; D = vapor diffusivity coefficient; K_v = hydraulic conductivity.

matric potential of soil water, hydraulic conductivity of the soil, gravity, and the temperature gradient (Fig. 4).

Because water has a high heat capacity and changes of phase influence heat transport, moisture is a significant modifier of temperature. Some workers have assumed that temperatures in moist soil will not rise above 100°C until water in any one layer has boiled off (DeBano et al. 1977, Aston and Gill 1976). More recent information (El-Doma et al. 1984, Frandsen and Ryan 1986) indicates that this plateau is more likely to be at about 80°C rather than at 100°C. The presence of moisture in the soil profile slows the rise in temperature compared to dry soils. More studies are needed to understand the processes of moisture-aided heat transfer at temperatures above 50°C.

MODELING HEAT TRANSFER FROM SOIL TO SOIL BIOTA

A limited number of published works deal with heat transfer in living tissue. Most articles have been devoted to heat transfer between the atmosphere and above ground plants, particularly leaves (Raschke 1960, Campbell 1977, Gates 1980) or within the stems of trees (Herrington 1969, Derby and Gates 1966, Martin 1963). Most studies that evaluated soil heating have focused on measuring or predicting soil temperature and have only inferred the relationship between the soil and biological structures. In some cases, temperatures of roots have been measured, but most often it has been assumed that soil residents are in equilibrium with the soil medium. The basic processes of heat transfer in the soil-plant or other organisms systems have not been described.

Conceptually, heat is transferred from each soil layer to the biota in that layer by the processes of conduction, mass movement of liquid, and vapor movement (Fig. 2). Movement of heat by conduction is probably the dominant process (Gates 1980, Raschke 1960, Campbell 1977), but liquid and vapor flux may be significant in some situations because moisture moves from the soil through parts of these structures (roots, mychorrizae, fungal hyphae). Heat transfer within the individual structures is also likely to be dominated by the process of conduction.

A number of variables are likely to influence heat transfer to the living structures and within these structures and thus influence responses (Fig. 5). Considerable work has been done to identify lethal temperature thresholds for living tissue (Baker 1929, Hare 1960, Levitt 1980, Flinn and Pringle 1983). In general, most plant tissue will die when exposed to temperatures of 55 to 60°C, also depending upon time at exposure.

Measurements of response to varying heating regimes in the laboratory and in the field have indicated that season of burning influences response, i.e., phenology or physiological state influences the response. Thus, lethal temperature thresholds may depend on phenological stage. Heat transfer rates, and thus mortality, may be altered by moisture differences or possibly the initial temperature level of the soil media. Observed response differences may also be due to differences in heat output of fires as influenced by fuel and atmospheric conditions associated with different seasons. The size (surface to volume ratio) of the biological structure is likely to influence the heat capacity, and thus the final temperature. Character of the outer surface will influence the thermal conductivity and thus the heat flow. Moisture content will influence the thermal properties and thus influence how phenological state, surface to volume ratios, and surface characteristics of the structure affect heat transfer.

In all likelihood, thermal equilibrium will be established rather quickly for small structures, such as fungi and other microorganisms, and small plant parts. In these cases, heat transfer analysis is probably not needed, and it will be sufficient to assume soil temperature and organism temperature will be equal. For larger structures such as large rhizomes, tubers, root crown, etc. heat transfer analysis will aid in understanding the processes and predicting the effects of soil heating.

Approach for Developing a Computer Model

The most desirable approach to quantify the conceptual model in Figure 2 would be to assemble and link models and algorithms that are already developed and tested. This may be possible for some of the components, particularly heat transfer in the soil. If models are not available, they will need to be developed from existing theory or the results of empirical studies.

In modeling heat transfer from fire to soil, guidance may be obtained from two models that have attempted to model heat flux or temperatures at the soil surface.

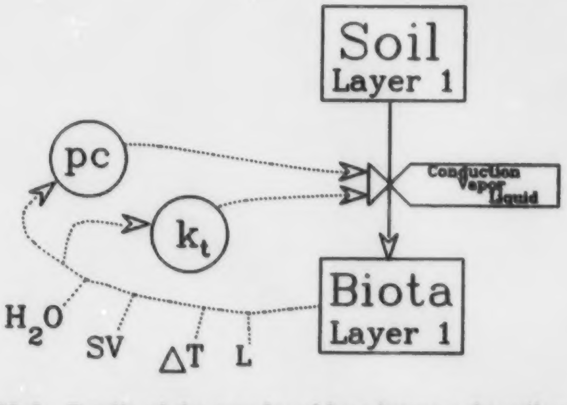


FIG 5. Details of the transfer of heat between the soil and roots or other biological material. The driving variables that influence the heat transfer processes are along the dotted lines. The circles represent calculated driving variables. Key to symbols: pc = heat capacity; k_t = thermal conductivity; H_2O = moisture content; SV = surface to volume ratio of structure; T = temperature gradient; L = latent heat of vaporization.

The model developed by Pafford et al. (1985) and Pafford (1986) predicts ground surface heating during prescribed burns in chapparal in southern California. The model assumes that no surface or organic layers are present. Calculations of heat from a moving flame front are used to calculate the energy balance at the soil surface, and a simple algorithm is used to calculate the absorption of heat by the soil. Radiant exchange of heat is emphasized, and natural convection of heat away from the surface is neglected. Work is needed to test this model and link it to fire behavior models.

The model by Chinanzvavana et al. (1986) and Chinanzvavana (1986) is a semi-empirical approach that calculates the heat flux at the ground surface as a fraction of heat released in burning. The heat flux from the fire is calculated from the mass and heat content of the fuel. The temperature profile at the surface is calculated from the fraction of the energy directed downward at the surface coupled with the algorithm that calculates heat transfer in the soil. This model may be useful for conditions where organic layers are present if the fraction of the heat released by burning can be evaluated for fires of different types.

Although a number of models of heat transfer in the soil have been developed, only four have attempted to model temperatures beneath fires (Scotter 1970, Aston and Gill 1976, Chinanzvavana et al. 1986, El-Doma et al. 1984). Scotter's (1970) first attempt did not account for the transfer of heat by liquid or vapor flow of water. The other investigators attempted to include heat transfer by movement of moisture. Aston and Gill (1976) and Chinanzvavana et al. (1986) used the assumption that the temperature of any layer would not rise above 100°C until all the moisture from the layer had evaporated. El-Doma et al. (1984) held temperatures at 80°C until all the moisture was evaporated. The 80°C threshold was based on experimental data and has also been observed by Frandsen and Ryan (1986).

Each of the modeling approaches used the same basic heat transfer equations, but solution of these equations was accomplished using different numerical techniques. Thermal conductivity and heat capacity are calulated in different ways, and solutions to the vapor transfer use different techniques. None of these models have been tested under field conditions, but some field data (Scotter 1970) was used by Aston and Gill (1976) to test their model. Temperature data from an experimental laboratory fire was used by El-Doma et al. (1984) to develop their model. Some preliminary tests with the Aston-Gill model using some existing data from laboratory fires show that the patterns for the temperature curves are similar to the observed data, but the rate of heat flow did not fit the observed data. Perhaps one of these models or some modification may be useful. As a first step, we plan to test the models against observed data and determine the sensitivity of the input parameters. Some laboratory and field testing is needed using typical forest soils, where moisture content, bulk density, and rates of heating can be varied. We are currently working with Dr. G. Campbell at Washington State University to test some of his models and develop a procedure for measuring moisture movement in the soil during the heating process.

References

ALBINI, F.A. 1975. An attempt (and failure) to correlate duff removal and slash fire heat. USDA For. Serv. Gen. Tech. Rep. INT-24. Intermt. For. Range Exp. Sta.

ASTON, A.R., and A.M. GILL. 1976. Coupled soil moisture, heat and water vapour transfers under simulated fire conditions. Aust. J. Soil Res. 14: 55-66.

BAKER, F.S. 1929. Effect of excessively high temperatures on coniferous reproduction. J. For. 27: 949-975.

BEADLE, N.C.W. 1940. Soil temperatures during forest fires and their effect on the survival of vegetation. J. Ecology. 28: 180-192.

BENTLEY, J.R., and R.L. FENNER. 1958. Soil temperatures during burning related postfire seedbeds on woodland range. J. For. 56: 737-740.

BRISTOW, K.L., G.S. CAMPBELL, R.I. PAPENDICK, and L.F. ELLIOTT. 1986. Simulation of heat and moisture transfer through a surface residue-soil system. Agric. For. Met. 36: 193-214.

BROWN, J.K., M.A. MARSDEN, K.C. RYAN, and E.D. REINHARDT. 1985. Predicting duff and woody fuel consumed by prescribed fire in the northern Rocky Mountains. USDA For. Serv. Res. Pap. INT-337. Intermt. For. Range Exp. Sta.

CAMPBELL, G.S. 1977. An introduction to environmental biophysics. New York: Springer-Verlag.

CHANDLER, C., P. CHENEY, P. THOMAS, L. TRABAUD., and D. WILLIAMS. 1983. Fire in forestry: Volume I--Forest fire behavior and effects. New York, Wiley.

CHINANZVAVANA, S. 1986. Numerical analysis of heat transfer in soil as applied during open field burning. Thesis. Wash. State Univ. Pullman.

CHINANZVAVANA, S., W.L. GROSSHANDLER, and D.C. DAVIS. 1986. Analysis of heat transfer in soil during open field burning. Transactions of the ASAE. 29(6): 1797-1801.

DERBY, R.W., and D.M. GATES. 1966. The temperature of tree trunks--calculated and observed. Amer. J. Bot. 53(6): 580-587.

DeBANO, L.F., P.H. DUNN, and C.E. CONRAD. 1977. Fire's effect on physical and chemical properties of chaparral soils. USDA For. Serv. Gen. Tech. Rep. WO-3.

DeBANO, L.F., R.M. RICE, and C.E. CONRAD. 1979. Soil heating in chaparral fires: effects on soil properties, plant nutrients, erosion, and runoff. USDA For. Serv. Res. Pap. PSW-145. Pacific SW For. Range Exp. Sta.

De VRIES, D.A. 1958. Simultanous transfer of heat and moisture in pourous media. Transactions, American Geophysical Union. 39(5): 909-916.

De VRIES, D.A., and N.H. AFGAN. 1975. Heat and mass transfer in the biosphere I. Transfer processes in plant environment. New York, Wiley Press.

EL-DOMA, M.O., B. LOCKE, D. PRIMACK, K. GOULD, J. LEGGOTT, S. BURNS, and R. KNAPP. 1984. Modelling heat and moisture transfer for prescribed fire in Southern California. Final Rep. The Mathematics Clinic, Claremont College. Riverside, CA.

FLINN, M.A., and J.K. PRINGLE. 1983. Heat tolerance of rhizomes of several understory species. Can. J. Bot. 61: 452-457.

FRANDSEN, W.H., and K.C. RYAN. 1986. Soil moisture reduces belowground heat flux and soil temperatures under a burning fuel pile. Can. J. For. Res. 16: 244-248.

GATES, D.M. 1980. Biophysical ecology. New York, Springer-Verlag.

HANKS, R.J., D.D. AUSTIN, and W.T. ONDRECHAN. 1971. Soil temperature estimation by a numerical method. Soil Sci. Amer. 35: 665-667.

HARE, R.C. 1960. Heat effects on living plants. USDA For. Serv. SO-183. Southern For. Exp. Sta.

HERRINGTON, L.P. 1969. On temperature and heat flow in tree stems. Bull. No. 73. School of Forestry, Yale University, New Haven, CT.

HEYWARD, F. 1938. Soil temperatures during forest fires in the longleaf pine region. J. For. 36(5): 478-491.

HUNGERFORD, R.D. 1987. Predicting response of understory vegetation to stand treatment: consequences for multiresource management. P. 118-136. In R.L. Barger, compiler, Management of small-stem stands of lodgepole pine--workshop proceedings; June 30-July 2, 1986, Fairmont Hot Springs, MT. USDA For. Serv. Gen. Tech Rep. INT-237. Intermt. Res. Sta.

KEANE, R.E. 1987. Forest succession in western Montana-a computer model designed for resource managers. USDA For. Serv. Res. Note INT-376. Intermt. Res. Sta.

LEVITT, J. 1980. Responses of plants to environmental stress: Volume I-chilling, freezing, and high temperature stresses. 2d ed. New York, Academic Press.

MARTIN, R.E. 1963. Thermal properties of bark. For. Prod. J. 13(10): 419-426.

MOEUR, M. 1985. COVER: a user's guide to the CANOPY and SHRUBS extension of the Stand Prognosis Model. USDA For. Serv. Gen. Tech. Rep. INT-190. Intermt. For. Range Exp. Sta.

MORGAN, P., and L.F. NEUENSCHWANDER. 1985. Modeling shrub succession following clearcutting and broadcast burning. P. 83-90. In J.E. Lotan, J.K. Brown, compilers, Fire's effects on wildlife habitat--symposium proceedings, March 21, 1984, Missoula, MT. USDA For. Serv. Gen. Tech. Rep.INT-186. Intermt. Res. Sta.

PACKHAM, D.R. 1969. Heat transfer above a small ground fire. Aust. For. Res. 5: 19-24.

PAFFORD, D.J. 1986. An investigation into ground surface heating during a prescribed burn. Thesis. Univ. of Calif., LA.

PAFFORD, D., V.J. DHIR, E.B. ANDERSON, and J. COHEN. 1985. A model for ground surface heating during a prescribed burn. P. 24-32. In Weather-the drive train connecting the solar engine to forest ecosystems: Proceedings of the Eighth Conference on Fire and Forest Meteorology; May 2-April 29, 1985, Detroit, MI.

RAISON, R.J., P.V. WOODS, B.F. JAKOBSEN, and G.A.V. BARY. 1986. Soil temperatures during and following low-intensity prescribed burning in a Eucalyptus pauciflora forest. Aust. J. Soil Res. 24(1): 33-47.

RASCHKE, K. 1960. Heat transfer between the plant and the environment. Annual Rev. Plant Phys. 11: 111-126.

ROWE, J.S. 1983. Concepts of fire effects on plant individuals and species. P. 135-154. In R.W. Wein, D.A. MacLean, eds., SCOPE 18: The role of fire in northern circumpolar ecosystems. Chichester, New York, John Wiley & Sons.

RYAN, K.C., and N.V. NOSTE. 1985. Evaluating prescribed fires. P. 230-238. In J.E. Lotan, B.M. Kilgore, W.C. Fischer, R.W. Mutch, tech. coords., Proc.--symposium and workshop on wilderness fire, November 15-18, 1983, Missoula, MT. USDA For. Serv. Gen. Tech. Rep. INT-182. Intermt. For. Range Exp. Sta.

SAMPSON, A.W. 1944. Effect of chaparral burning on soil erosion and soil moisture relations. Ecology. 25(2): 171-191.

SCOTTER, D.R. 1970. Soil temperatures under grass fires. Aust. J. Soil Res. 8:73-279.

SHEARER, R.C. 1975. Seedbed characteristics in western larch forests after prescribed burning. USDA For. Serv. Res. Pap. INT-167. Intermt. For. Range Exp. Sta.

SHEARER, R.C. 1976. Early establishment of conifers following prescribed broadcast burning in western larch/Douglas-fir forests. P. 481-500. In Proceedings, Tall Timbers fire ecology conference and Intermountain Fire Research Council fire and land management symposium No. 14; October 8-10, Missoula, MT, Tallahassee, FL: Tall Timbers Res. Sta.

STATHERS, R.J., T.A. BLACK, and M.D. NOVAK. 1985. Modelling soil temperature in forest clearcuts using climate station data. Agric. For. Met. 36: 153-164.

TARRANT, R.F. 1956. Effects of slash burning on some physical soil properties. For. Sci. 2(1): 18-22.

WELLS, C.G., R.E. CAMPBELL, L.F. DeBANO, and others. 1979. Effects of fire on soil: a state of knowledge review. USDA For. Serv. Gen. Tech. Rep. WO-7.

WESTCOT, D.W., and P.J. WIERENGA. 1974. Transfer of heat by conduction and vapor movement in a closed soil system. Soil Sci. Soc. of America Proceedings. 38: 9-14.

WIERENGA, P.J., and C.T. DeWITT. 1970. Simulation of heat transfer in soils. Soil Sci. Soc. of America Proceedings. 34: 845-848.

Fuel Consumption From Prescribed Fire in Northern Idaho Logging Slash

E.D. REINHARDT, J.K. BROWN, AND W.C. FISCHER
Intermountain Research Station
Forest Service, U.S. Department of Agriculture
Missoula, Montana

Abstract

Experimental burns were conducted on 35 plots in grand-fir/western white-pine/western-hemlock logging slash near Coeur d'Alene, Idaho, to investigate consumption of duff and woody fuel. The study site was a series of small harvest units on a steep, north-facing slope in the Deception Creek Experimental Forest. Fires were conducted in spring and fall, in YUM (yarded unmerchantable material) and non-YUM clearcuts and seed-tree cuts. Preburn and postburn fuel loadings were measured, and fuel moistures were sampled shortly before ignition. Regression relationships are summarized. The preburn duff depth in this area averaged 3.8 cm. It consisted of a shallow layer of decomposing litterfall, averaging 2 cm, interspersed with deep pockets of rotten wood averaging 13 cm. Duff depth reduction was related to preburn duff depth, but not to duff moisture content or National Fire Danger Rating 1000 hour fuel moisture index. Percent duff consumption and mineral soil exposure were related to duff moisture and large fuel diameter reduction. Large woody pieces ranged from 8 to 68 cm in diameter; 77% were sound and 23% were rotten. Plot average diameter reduction of large logs was positively related to preburn diameter and negatively related to log moisture content. Consumption of rotten material was greater than sound. Consumption of individual logs was extremely variable and weakly correlated with piece diameter, moisture content, distance to the soil, or distance to other large pieces. It was not related to species, degree of rot, or presence or absence of bark. The relationships developed through regression can be used to predict duff and fuel consumption for prescribed burns in the western white pine type of the northern Rocky Mountains.

Résumé

Des brûlages expérimentaux ont été effectués dans 35 parcelles jonchées de déchets de coupe de sapin grandissime/occidental pin-blanc/cigue-occidental près de Couer d'Alene en Idaho pour connaître la consumation d'humus et de combustibles ligneux. Le site d'étude se composait d'une série de petites unités d'exploitation occupant un versant abrupt exposé au nord dans la forêt expérimentale de Deception Creek. Les brûlages ont été réalisés au printemps et à l'automne dans des parterres de coupe rase et des unités de semenciers et dans des unités à matériel non commercialisable débusqué et non débusqué. La biomasse de combustible avant et après le brûlage a été mesurée et la teneur en humidité des combustibles a été échantillonnée avant l'allumage. Un résumé des relations de régression vient ensuite. Dans ce secteur, la couche d'humus du pré-brûlage avait une épaisseur moyenne de 3,8 cm. Elle se composait d'une couche superficielle de litière en décomposition de 2 cm en moyenne, parsemée de poches profondes de bois pourri d'une épaisseur moyenne de 13 cm. La diminution de l'épaisseur de l'humus était corrélée à de l'humus, mais non pas à la teneur en humidité de la partie inférieure de la couche d'humus ou à l'indice d'humidité de 1000 heures du national Fire Danger Rating. Le pourcentage de consumation de l'humus et d'exposition du sol minéral a été corrélé à la teneur en humidité de la partie supérieure de la couche d'humus et à une diminution du diamètre des combustibles lourds. Le diamètre des combustibles lourds variait de 8 à 68 cm; 77 % d'entre eux étaient sains et 23%, pourris. La réduction du diamètre moyen des grosses grumes de parcelle a été corrélée positivement au diamètre pré-brûlage et négativement à la teneur en humidité des grumes. Une plus forte proportion de combustible pourri que de combustibles sains a été consumée par le feu. La consumation était extrêmement variable d'une grume à l'autre et faiblement corrélée avec le diamètre du morceau de^bois, la teneur en humidité ou l'éloignement du sol ou à d'autres grumes plus grosses. Aucune relation avec l'essence, le degré de pourriture ou la présence ou l'absence d'écorce n'a été établie. Le relation établie à travers la régression peut servir à prédire la consumation d'humus et de combustibles pour des brûlages dinigés au type de pin-blanc de l'ouest des montagnes rocheuses situées au nord.

Introduction

In the northern Rocky Mountains, prescribed fire is commonly used following harvest cutting to reduce fire hazard from logging debris and to prepare sites for conifer regeneration. To accomplish these objectives, the fire must be conducted under conditions that result in consumption of specified amounts of duff and woody debris, and sometimes mineral soil exposure. The prescribed fire specifications often include upper limits on duff consumption, woody fuel

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

consumption, and mineral soil exposure in order to maintain site productivity. Excessive mineral soil exposure or heating may leave the site vulnerable to erosion or cause soil damage. Residual duff and woody material may be important for long-term nutrient cycling and ectomycorrhizal relationships (Harvey et al. 1987). Residual large woody fuels can also minimize soil movement, provide shade for seedling establishment, and enhance wildlife habitat. Minimizing large fuel and duff consumption can mitigate smoke emissions.

Previous studies have documented correlations between duff moisture and both duff consumption and mineral soil exposure. Several studies (Norum 1977, Sandberg 1980, Shearer 1975) suggested three general patterns of duff consumption; very dry duff (moisture content < 30%) will burn independently once ignited and complete consumption can be expected. Very wet duff (moisture content > 120%) will probably not burn well under any circumstances. At intermediate moistures, the amount of duff consumed can be expected to vary with moisture and with the amount of heat from surface fires (Ottmar et al. 1985). In the northern Rocky Mountains, lower duff moisture has been found to correlate especially well with duff consumption (Brown et al. 1985). Other predictors of duff consumption used with varying degrees of success are average duff moisture, humus layer moisture, National Fire Danger Rating (NFDR) 1000-h fuel moisture, days since rain, diameter reduction of woody fuel, consumption of large woody material, consumption of large woody material divided by its moisture content, and preburn duff depth (Brown et al. 1985, Harrington 1987, Little et al. 1986, Ottmar et al. 1985, Sandberg 1980).

Mineral soil exposure obviously is closely related to duff consumption, and can be predicted from duff consumption (Brown et al. 1985, Sandberg 1980), and from many of the same variables used to predict duff consumption. Large woody fuel consumption has been predicted mainly from unit average preburn diameter and some measure of large woody fuel moisture: measured moisture, NFDR 1000-h fuel moisture, or specially adjusted values of NFDR 1000-h fuel moisture (Sandberg and Ottmar 1983).

The objectives of this study were to characterize postharvest fuels, and to investigate duff and woody fuel consumption from prescribed fire in northern Idaho grand-fir/western-white-pine/western-hemlock logging slash. None of the previously existing prediction equations for duff consumption, mineral soil exposure, and woody fuel consumption was developed or tested in this forest type. Prescribed fires were conducted under a range of fuel moisture conditions and fuel loadings to investigate their effects on consumption. We tested existing prediction equations and developed new equations to predict duff consumption, mineral soil exposure, and woody fuel consumption.

The Study Area

The study was conducted in the Deception Creek Experimental Forest, Idaho Panhandle National Forests, near Coeur d'Alene, Idaho. The study site is a series of small logging units on a steep (50-80%) north-facing slope along Deception Creek. Elevation is between 900 and 1200 m. Precipitation at Deception Creek averages 142 cm annually; about 25% of it is in the form of snow. Snow cover usually lasts from November to late April (Finklin and Fischer 1987).

The study site has a western white pine cover type (SAF cover type 215) (Society of American Foresters 1980). Habitat types in the area are Tsuga heterophylla/Clintonia uniflora-Clintonia uniflora phase and Xerophyllum tenax phase (Cooper et al. 1987). Predominant conifer species are grand fir (Abies grandis), white pine (Pinus monticola), and western hemlock (Tsuga heterophylla); smaller amounts of western larch (Larix occidentalis) and Douglas fir (Pseudotsuga menziesii) are present.

Units were harvested and unmerchantable trees were felled one to two seasons before the fire treatments. Harvest methods used were clearcuts and seed-tree cuts. In 12 units fuel loadings were reduced by applying a "YUM" treatment: unmerchantable material greater than 15 cm in diameter was yarded to the tops of the units and made available to firewood cutters, resulting in lighter than normal preburn fuel loadings and additional duff and soil disturbance. Units were burned in late spring, late summer, and fall to provide a range of moisture conditions and fire treatments. The prescribed fires were conducted by Fernan Ranger District personnel. The fires were strip-head fires ignited using propane torches. Many of the fires were ignited in the early evening to reduce risk of escape during the wildfire season.

Methods

Forty-four plots, each about 0.5 to 1 ha, were established. In some harvest units, more than one plot was defined: above and below a road for example, or on either side of a small draw with an associated change in aspect. Nine of the plots were reserved as unburned controls.

DATA COLLECTION

In each plot, 20 sample points were permanently marked. Each point had a permanent 15.24-m transect associated with it for inventory of down woody fuel (Brown 1974). Eight duff spikes were driven into the soil around each sample point, with their heads flush with the duff surface.

In 18 of the plots, 60 logs were circled with wire for diameter reduction measurement (Hedin and Turner 1977). Logs selected were at least 7.62 cm in diameter. The first three logs intersected by each of the 20 fuel transects were selected. Species, presence or absence of bark, degree of rot, distance from the ground, and distance from other large woody material were recorded.

Immediately before the burns, moisture contents of duff, 0-0.6 cm twigs, and 0.6-2.5 cm twigs were sampled. It was impractical to separate the duff into upper and lower layers for moisture sampling. Instead, we sampled moisture of the usually shallow layer of decaying litterfall, and moisture of deep pockets of rotten wood. A slice was sawed from each wired log for moisture content determination. All samples were oven dried for moisture content determination.

Postburn measurements included a reinventory of the woody fuel transects and measurements of duff consumption and residual duff depth at each of the duff spikes. Depth of char as defined by Ryan and Noste (1984) was recorded for 40 sample locations in each plot. Wires on the logs were measured to determine preburn circumference. They were cinched up and measured to determine postburn circumference.

ANALYSIS

Analysis consisted of characterization of fuels, comparison of fuel consumption and mineral soil exposure with that predicted by previous studies, and development of prediction equations for estimating fuel consumption and mineral soil exposure. Predicted consumption from previous studies was compared to observed consumption by examining the average magnitude of the difference between predicted and observed values (|predicted - observed|/ sample size), and the average bias or over- or underprediction of the equations ((predicted - observed) / sample size). New prediction equations were generated using multiple linear regression.

Results and Discussion

GROUND CHAR

Most of the burned area was classified as having moderate ground char: litter, duff and small woody materials were almost completely consumed, leaving a light colored ash, but the mineral soil was not visibly altered. A small amount of the area had little duff or litter before the burns, and experienced only light ground char. The surface of the ground appeared blackened, but many twigs and fragments of duff remained essentially unaltered by the fire. Another small part of the area near burned-out stumps or below large logs was classified as having deep ground char. In these areas, the surface of the mineral soil was reddened, and organic material in the mineral soil was blackened.

Depth of ground char appeared to be determined not by fuel moisture conditions, but by preburn fuel loadings and characteristics: the presence of a continuous layer of duff and litter distinguished areas of moderate ground char from areas of light ground char; the presence of rotting stumps or piles of logs characterized areas of deep ground char.

DUFF COSUMPTION

Preburn duff depth at Deception Creek averaged 3.8 cm. It consisted of a shallow (mean = 2 cm) layer of decomposing litterfall ("shallow duff"), interspersed with pockets of rotten wood averaging 13 cm deep ("deep rotten wood"). The deep rotten wood covered an average of 13% of the forest floor.

Mineral content of the shallow duff was 44.8%, as determined by ashing. Bulk density was .14 g/cm^3.

Average moisture content of the shallow duff ranged from 9% to 40% on the 35 plots, averaging 21%. Moisture of the deep rotten wood was much greater. In the fall of 1984, when only 0.76 cm of rainfall had been recorded since the end of June, moisture contents over 200% were still being observed in these pockets. Plot averages ranged from 58% to 300%, with a mean of 176%.

Consumption of the duff was fairly complete. The median residual duff depth was 0 on 19 of the 35 plots, and exceeded 1 cm on only two plots.

Percentage duff consumption observed at Deception Creek was greater than that predicted by most of the equations in the literature using NFDR 1000-h fuel moisture, lower duff moisture, humus layer moisture, preburn duff depth, and consumption of large woody material as independent variables. It was predicted well by Brown's 1985 equation for sites in the northern Rocky Mountains, when moisture content of the shallow duff layer was used for average duff moisture:

$$DR\% = 83.7 - 0.426\ ADM \qquad (1)$$

where DR% = duff consumption, %;
ADM = average duff moisture content, %

For the 35 burned plots, the average magnitude of the deviations between observed duff consumption and that predicted by this equation was 10.7%. The bias was only 1.47%.

The best descriptive relationship for percentage duff consumption generated from the Deception Creek data was:

$$DR\% = 59.6 - 0.346\ DM + 2.782\ WR \qquad (2)$$

where DM = shallow duff moisture,%;
WR = plot mean diameter reduction of large woody material, cm.

($r^2 = 0.46$, s.e.= 8.4%)

Figure 1 shows the relationship between percentage duff consumption and moisture content as modeled by these two equations. The presence of diameter reduction of large woody material in the Deception Creek equation suggests the importance of heat from surface fire in driving off duff moisture and increasing duff consumption. Consumption of large woody material has been found to be an important predictor of duff consumption in the Pacific Northwest (Little et al. 1986, Ottmar et al. 1985).

Duff depth reduction, unlike percentage duff consumption, was mostly overpredicted by equations

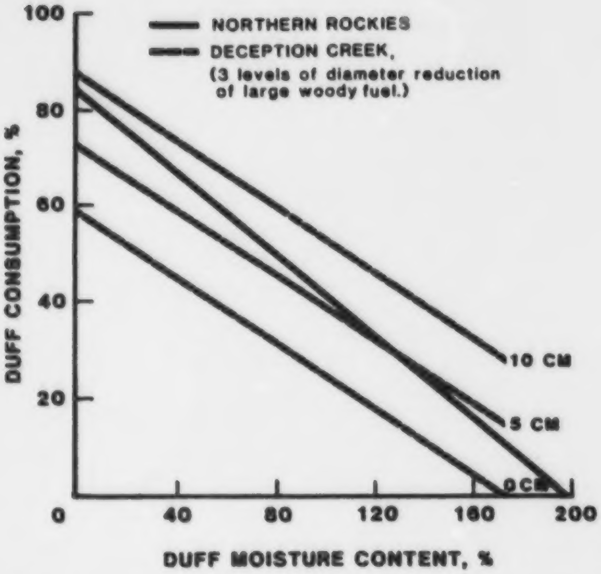


FIG 1. The relationship between percentage duff consumption and duff moisture content, for the Northern Rocky Mountains (Equation 1), and for three levels of diameter reduction of large woody fuel at Deception Creek (Equation 2).

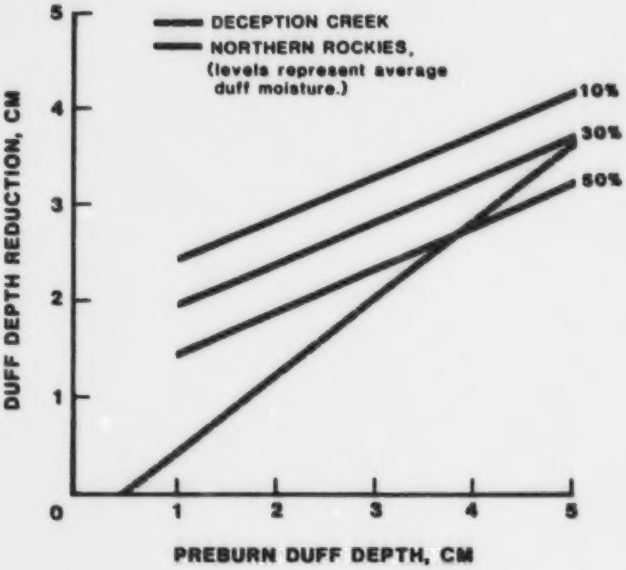


FIG 2. The relationship between duff depth reduction and preburn duff depth for three levels of average duff moisture in the northern Rocky Mountains (Equation 3), and for Deception Creek (Equation 4).

in the literature. This apparent inconsistency is explained by the relatively complete consumption of a duff layer shallower than in those previous studies. Of the equations in previous work for predicting duff depth reduction, the best fit with Deception Creek data was obtained with Brown's 1985 equation using average duff moisture content and preburn duff depth:

$$DR = 2.238 - 0.0244\ ADM + 0.439\ PRE \qquad (3)$$

where DR = duff depth reduction, cm; PRE = preburn duff depth, cm.

Predictions generated by this equation differed from observed values at Deception Creek by an average magnitude of 0.56 cm, with a bias of only 0.25 cm. Slightly better fit could be obtained with the equation generated from Deception Creek data:

$$DR = -0.341 + 0.786\ PRE \qquad (4)$$

$(r^2 = 0.73,\ s.e. = 0.46\ cm)$

Duff moisture content was not an important variable in combination with preburn duff depth. At the range of moistures encountered, duff consumption was fairly complete, and not dependent on duff moisture. The amount of duff consumed depended mostly on how much was available for consumption. Equations 3 and 4 are plotted in Figure 2.

No differences in duff consumption were observed between YUM and non-YUM units, although the YUM process resulted in some disturbance of the duff.

MINERAL SOIL EXPOSURE

Residual duff depths less than 1 cm were considered mineral soil for this analysis. Previous work suggested that residual duff depths of this magnitude can provide an adequate bed for germinating seedlings, because most seedlings can penetrate through this amount of residual duff and reach mineral soil, and because the duff continues to deteriorate after fire (Brown et al. 1985).

In part because preburn duff depths were so shallow, mineral soil exposure was fairly extensive. Mineral soil exposure was not related to depth of ground char, because most areas with light ground char probably met the mineral soil criterion before the fires, and most areas with moderate or severe ground char had nearly complete duff consumption and mineral soil exposure. For the most part, areas where mineral soil was not exposed were pockets of deep rotten wood, which were often incompletely burned.

Of the equations in the literature for predicting mineral soil exposure, the best fit with Deception Creek data was obtained with Brown's 1985 equation:

$$MSE = -8.98 + 0.899\ DR\% \qquad (5)$$

where MSE = mineral soil exposure, %

Good fit was also obtained using the equation:

$$MSE = 167.4 - 31.6 \ln(ADM) \qquad (6)$$

from the same source. These equations predicted mineral soil exposed by fire essentially as well as any new equations generated from the data.

LARGE WOODY FUEL CONSUMPTION

Large woody fuel was defined to be material with a diameter greater than 7.62 cm. Preburn large woody fuel loadings ranged from 41,400 to 120,500 kg/ha on YUM plots and 45,900 to 172,500 kg/ha on the non-YUM plots. Large woody fuel consumption ranged from 11.8% to 64.5% on the 35 plots.

Large woody fuel consumption was expressed as diameter reduction and as percent volume consumption. On an individual piece basis, both measures of consumption were extremely variable and only weakly correlated with moisture content, preburn diameter, distance to the ground, or distance to other large woody material.

Plot average diameter reduction of large woody material was compared to diameter reduction predicted by Sandberg and Ottmar's 1983 equation:

$$WRIN = 5.68 - .108\ MC \qquad (7)$$

where WRIN = diameter reduction of large woody material, inches;

MC = plot average moisture content of large woody material, %

This equation was developed for logging slash (sound material only) in western Oregon and Washington. Observed moisture contents of sound woody material were greater at Deception Creek than in the earlier study, and greater diameter reduction occurred at a given moisture content. The average difference or bias between observed plot average diameter reduction and that predicted by Sandberg and Ottmar's equation was 6.43 cm. If sound logs with measured moistures greater than 60% were eliminated from the plot averages, this difference would be reduced to 0.93 cm. The upper limit of observed moisture contents in Sandberg and Ottmar's study was 60%; at Deception Creek almost 10% of the sound logs had moisture contents greater than 90%.

Sandberg and Ottmar reported that average moisture content alone was a very good predictor of average diameter reduction. This was not true in our study. The r^2 value for the regression of average diameter reduction on average moisture content for sound logs was only 0.15. Plot average preburn diameter, although only weakly correlated with diameter reduction (r^2 for the regression was 0.08), was an important predictor in combination with moisture content. Greater average diameter reduction was observed in plots with greater average preburn diameter (Figure 3). The best prediction equation we generated for average diameter reduction of sound woody fuel was:

$$WR = 3.350 + 0.607\ PRED - 0.241\ MC \qquad (8)$$

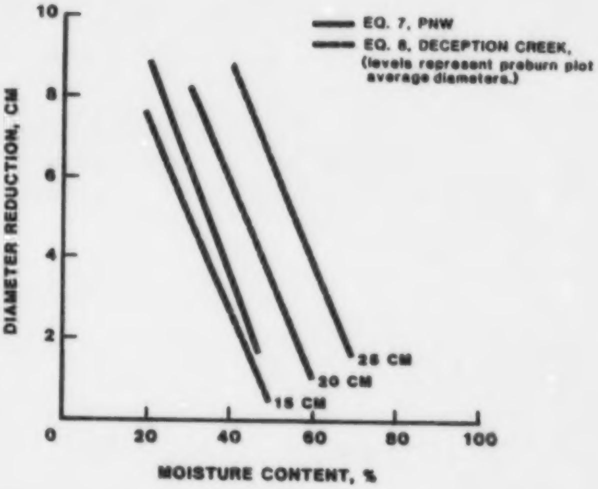


FIG 3. The relationship between diameter reduction of large woody fuels for the Pacific Northwest (Equation 7) and for three levels of average preburn diameters at Deception Creek (Equation 8).

where PRED = plot average preburn diameter of large woody material, cm.

$$(r^2 = .65,\ s.e. = 1.31\ cm.)$$

Preburn diameter may have been an important variable at Deception Creek because so many of the logs of all sizes burned completely. The presence of bigger logs that were completely consumed may have raised the plot average diameter reduction.

Consumption of rotten material was greater than of sound, although it was much wetter. The mean moisture content of rotten logs was 30% higher than of sound, and average diameter reduction was 1.5 cm greater.

FUEL MOISTURE: PREDICTED VS. OBSERVED

Average measured moisture content of sound pieces was not strongly correlated with NFDR 1000-h fuel moisture index ($r = 0.51$). Ottmar and Sandberg's 1983 adjustment to the NFDR 1000-h fuel moisture index was somewhat better correlated with measured moistures ($r = 0.66$). Neither the NFDR 1000-h moisture index nor the adjusted NFDR 1000-h moisture index were as well correlated with diameter reduction as measured moisture content was.

Conclusions

Results of this study indicate that it may be difficult to conduct slash burns in this forest type and retain very much duff. Duff consumption was not strongly dependent on duff moisture. The shallow duff layer was mostly consumed under the full range of operational conditions tested. If residual organic material is a concern, managers should concentrate on protecting the pockets of deep rotten wood. These appear to remain wet throughout the burning season even in dry summers. Alternatively, managers could prescribe fires that are discontinuous due to high moisture content of fine woody fuels. In this way the shallow duff layer could be retained in unburned patches.

Large woody fuel consumption in this forest type was less strongly dependent on moisture content than in stands in the Pacific northwest. Woody fuel was consumed even under relatively high moistures.

References

BROWN, J.K. 1974. Handbook for inventorying downed woody material. USDA For. Serv. Gen. Tech. Rep. INT-16, Intermt. For. and Range Exp. Sta..

BROWN, J.K., M.A. MARSDEN., K.C. RYAN, AND E.D. REINHARDT. 1985. Predicting duff and woody consumption in the northern Rocky Mountains. USDA For. Serv. Res. Pap. INT-337, Intermt. For. and Range Exp. Sta..

COOPER, S.V., K.E. NEIMAN, R. STEELE, AND D.W. ROBERTS. 1987. Forest habitat types of northern Idaho: a second approximation. USDA For. Serv. Gen. Tech. Rep. INT-236, Intermt. Res. Sta.

FINKLIN, A.I. AND W.C. FISCHER. 1987. Climate of the Deception Creek Experimental Forest, Northern Idaho. USDA For. Serv. Gen. Tech. Rep. INT-226, Intermt. For. and Range Exp. Sta..

HARRINGTON, M.G. 1987. Predicting reduction of natural fuels by prescribed burning under ponderosa pine in southeastern Arizona. USDA For. Serv. Res. Note RM-472, Rocky Mount. For. and Range Exp. Sta.

HARVEY, A.E., M.F. JURGENSEN, M.J. LARSEN, AND R.T. GRAHAM. 1987. Decaying organic materials and soil quality in the Inland Northwest: a management opportunity. USDA For. Serv. Gen. Tech. Rep. INT-225, Intermt. Res. Sta.

HEDIN, A. AND T. TURNER. 1977. What is burned in a prescribed fire? DNR Note 16. Wash. Dept. of Nat. Resour.

LITTLE, S.N., R.D. OTTMAR, AND J.L. OHMANN. 1986. Predicting duff consumption from prescribed burns on conifer clearcuts in western Oregon and western Washington. USDA For. Serv. Res. Pap PNW-362, Pac. Northwest For. and Range Exp. Sta.

NORUM, R.A. 1977. Preliminary guidelines for prescribed burning understanding timber in western larch/Douglas-fir forests. USDA For. Serv. Res. Note INT-229, Intermt. For. and Range Exp. Sta..

OTTMAR, R.D., S.N. LITTLE, AND J.L. OHMANN. 1985. Predicting duff reduction to reduce smoke from clearcut slash burns in western Washington and western Oregon. 8th Conf. on Fire and For. Meteor.

OTTMAR, R.D., AND D.V. SANDBERG. 1983. Estimating 1000-hour fuel moistures in the Douglas-fir subregion. 7th Conf. on Fire and For. Meteor.

RYAN, K.C. AND N.V. NOSTE. 1984. Evaluating prescribed fires. Proceedings--symposium and workshop on wilderness fire. USDA For. Serv. Gen. Tech. Rep. INT-182, Intermt. For. and Range Exp. Sta. pp. 230-238.

SANDBERG, D.V. 1980. Duff reduction by prescribed underburning in Douglas-fir. USDA For. Serv. Res. Pap. PNW-272, Pac. Northwest For. and Range Exp. Sta.

SANDBERG, D.V. AND R.D. OTTMAR. 1983. Slash burning and fuel consumption in the Douglas-fir subregion. Proceedings, 7th Conf. on Fire and For. Meteor.

SHEARER, R.C. 1975. Seedbed characteristics in western larch forests after prescribed burning. USDA For. Serv. Res. Pap. INT-167, Intermt. For. and Range Exp. Sta..

SOCIETY OF AMERICAN FORESTERS. 1980. Forest cover types of the United States and Canada. (F.H. Eyre, ed.)

Survival and Growth of Young Southern Pine After Simulated Crown Scorch

D.R. WEISE
Pacific Southwest Forest
USDA Forest Service
Riverside, California

D.D. WADE
Range Experiment Station
USDA Forest Service
Macon, Georgia

R.W. JOHANSEN
Southeastern Forest Experiment Station
USDA Forest Service
Macon, Georgia

Abstract

The effects of defoliation level and timing on growth and survival of young loblolly (Pinus taeda L) and slash (P. elliottii Engelm.) pines were studied in pine plantations in 1986. Five defoliation levels (100, 95, 66, 33, or 0 percent) and four defoliation times (January, April, July or October) were replicated at four Coastal Plain locations (two in Georgia and one each in Florida and South Carolina). Needles were manually removed from the ground up through the crown to simulate scorch effects on foliage. Ninety-three percent of the loblolly pines defoliated 100% in October and 40% of the slash pines defoliated 100% in October were killed. Diameter and height growth of trees defoliated at the three most severe levels were reduced.

Résumé

Une étude était entreprise en 1986 pour déterminer les effets du degré et de la période de défoliation sur le taux de croissance et de survie de jeunes pins taedas (Pinus taeda L.) et pins d'Elliot (Pinus elliottii Engelm.) Quatre endroits de la plaine côtière (2 en Georgie, un en Floride et un autre en Caroline du Sud) ont été soumis à cinq degrés de défoliation (100, 95, 66, 33 ou 0%) à quatre périodes de défoliation différentes (janvier, avril, juillet ou octobre), traitements assortis de répétitions. Les aiguilles ont été enlevées à la main, de la base au sommet de la cime, pour simuler les effets du roussissement sur le feuillage. Un taux de mortalité de 93% a été observé chez les pins taedas ayant été complètement défoliés en octobre et 40% des pins d'Elliot ayant été complètement défoliés en octobre sont morts. Les arbres soumis aux trois plus importants degrés de défoliation présentaient toutefois une diminution significative de l'accroissement de leur diamètre et de leur hauteur.

Introduction

Prescribed fire is used extensively in the southern United States to manage southern pine stands. This practice, as well as wildfire, sometimes can result in damage to crop trees. Roots, stems, and crowns can be individually or collectively affected. Knowledge of the magnitude and duration of a tree's response to various levels of damage is a prerequisite for evaluating management alternatives. Wade and Johansen (1986) reported that the factors affecting postfire survival and growth of southern pine have not yet been adequately described and in fact are often contradictory. Growth reductions and increases as well as differing mortality have been reported for identical levels of scorch (Villarubia and Chambers 1978, Waldrop and Van Lear 1984). A study was established in January 1986 to better delineate the effects of timing and severity of crown defoliation on southern pine survival and growth.

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

Methods

To study the survival and growth of young southern pines after simulated crown scorch, this study was established in 4-year-old loblolly (Pinus taeda L.) and slash (P. elliottii Engelm.) pine plantations on the South Carolina, Georgia, and Florida coastal plain in 1986. A factorial experiment with 15 replications was established at each of 4 locations. Loblolly pine sites were established at Bainbridge, Ga. and Branchville, S.C. and slash pine sites at Palatka, Fl. and Waycross, Ga. in January. Study trees were 2.5 to 3.5 meters tall, healthy, and of good form at the time of selection. One of five levels of defoliation (0, 33, 66, 95, and 100 percent) and one of four timings of defoliation (January, April, July, or October) were randomly assigned to each of 20 trees within a replication (fig.1).

Foliage was removed manually during the first two weeks of April, July or October 1986 or January 1987. Foliage removal began at ground level and progressed up through the crown to simulate crown scorch. This technique simulated the effects of foliage drop resulting from prescribed fire without incorporating any heat effects (i.e. heat damage to buds). Needles, sheaths, and fascicles were stripped off of branches and the bole. Care was taken not to accidently remove any buds during the stripping process.

Initial tree diameter at breast height (d.b.h., 1.37 m above ground) and total height were measured in early 1986 before bud elongation. D.b.h. and total height were remeasured in January of 1987, 1988, and 1989. Survival of each tree was noted by observing bud condition. The number of annual growth flushes was recorded at selected locations and times. Mean initial height and d.b.h. did not differ between defoliation levels or timings. A wildfire burned through a portion of the Branchville site during the winter of 1987. Survival of the trees unaffected by the wildfire was similar to survival at Bainbridge.

Analysis of variance (ANOVA) was used to test for differences in final d.b.h. and height for each level and timing of defoliation. As expected, the interactions between timing and level of defoliation were significantly different from 0. Selected line plots of mean d.b.h. and height were graphed by location by timing of defoliation (figs. 2-5). The terms d.b.h. growth rate and height growth rate refer to the slopes of these line plots.

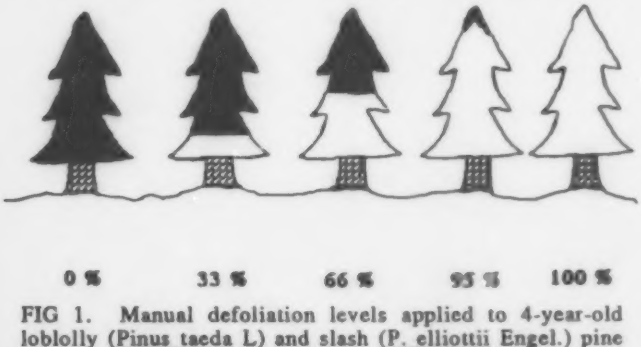


FIG 1. Manual defoliation levels applied to 4-year-old loblolly (Pinus taeda L) and slash (P. elliottii Engel.) pine in the coastal plain of South Carolina, Georgia, and Florida.

Table 1. Effects of defoliation level and timing on diameter and height of 4-year-old loblolly (Pinus taeda L) and slash (P. elliottii Engelm.) pines in the South Atlantic Coastal Plain.

	Growth Variable[1]	
Pine species	Diameter	Height
Loblolly (Bainbridge)	L, T	L, T, L*T
Slash (Palatka)	L, T, L*T	L, L*T
Slash (Waycross)	L, T, L*T	L, T. L*T

[1] Letters indicate significant factors in ANOVA (P <= 0.025). L = defoliation level (0, 33, 66, 95, or 100 percent crown defoliation), T = defoliation timing (within first 2 weeks of April, July, or October 1986 or January 1987), L*T = interaction between defoliation level and timing.

Results

Defoliation level significantly altered d.b.h. and height of slash and loblolly pine at all three sites ($P < 0.01$) (table 1). Timing of defoliation significantly altered d.b.h. and height at Waycross and Bainbridge, but not Palatka. The interactions between level and timing were statistically significant ($P < 0.05$) for slash pine d.b.h. and height, and for loblolly pine d.b.h. (table 1). In both species, d.b.h. and total height growth loss increased as defoliation increased. Severe defoliation (95 and 100 percent) contrasted with no defoliation. Results for the moderate defoliations (33 and 66 percent) followed the general trends that severe defoliation did; however, growth reductions were not as numerically large. These are preliminary results and mean separation techniques such as Duncan's Multiple Range have not been used. Thus the growth reductions may or may not all be statistically different.

SLASH PINE

Growth patterns at Waycross and Palatka were similar so only Palatka results are presented graphically. Undefoliated trees had the greatest mean d.b.h. (fig. 2). Complete defoliation reduced d.b.h. by 12 to 33 percent (table 2). The 66 percent defoliations reduced d.b.h. by up to 16 percent.

D.b.h. growth rate, indicated by slope of the line plots, recovered within 12 months for all defoliations except the complete October defoliation (fig. 2). April and July treatments, applied during the growing season,

Table 2. Loss of diameter and height growth due to seasonal defoliation of young slash pine (*Pinus elliottii* Engelm.) in the Florida and Georgia coastal plain.

Defoliation timing	Site[1]	Defoliation level (pct)[2] 66	95	100
January	P	11(3)	23(15)	23(14)
	W	7(4)	18(13)	26(21)
April	P	7(3)	11(9)	13(9)
	W	6(6)	6(10)	12(13)
July	P	8(1)	15(10)	21(18)
	W	16(10)	14(10)	20(17)
October	P	7(3)	21(13)	33(22)
	W	14(8)	22(18)	27(24)

[1] P = Palatka, Fl.; W = Waycross, Ga.

[2] Percentage of foliage hand removed from ground upward.

depressed d.b.h. growth rate in the same growing season that defoliation occurred. D.b.h. growth rate reduction was not apparent until the growing season following the October and January treatments -- dormant season applications.

Slash pine total height was also reduced by defoliation (fig. 3). Total height of the complete defoliations was reduced 9 to 24 percent (table 2). January and April defoliations reduced height growth rate in the growing seasons of defoliation. July and October growth reductions occurred during the growing season after treatment. This result is not considered surprising as height growth is primary growth and occurs early in the growing season. Sixty-five percent of the height growth of southern pine seedlings in North Carolina was completed by July 1 (Kramer 1943).

Forty percent of the trees completely defoliated in October died by January 1989 at Palatka. Slash pine mortality did not occur at Waycross or in partially defoliated trees at Palatka. No sign of disease or insect attack was observed at Palatka so mortality was attributed to the defoliation treatment.

LOBLOLLY PINE

As with slash pine, defoliation reduced d.b.h. (fig. 4). D.b.h. growth of the trees treated in January and April recovered the next growing season. July d.b.h. growth rate recovered two growing seasons after defoliation. The complete October defoliation growth rate has yet to recover. D.b.h. of the completely defoliated trees was reduced 7 to 57 percent (table 3).

January and April height growth rates were reduced in the growing season of treatment; July and October height growth rates the following growing season (fig. 5). The total height of completely defoliated trees was reduced 14 to 48 percent (table 3). Except for the complete October defoliation, height growth rate of all treatments has recovered.

Table 3. Loss of diameter and height growth due to seasonal defoliation of young loblolly pine (*Pinus taeda* L) in the Georgia coastal plain.

Defoliation timing	Defoliation level (pct)[1] 66	95	100
January	0(4)	8(17)	11(14)
April	5(11)	7(13)	10(16)
July	1(7)	5(14)	7(18)
October	2(11)	12(23)	57(48)

[1] Percentage of foliage hand removed from ground upward.

Mortality was observed in only one category: the complete October defoliation. Since no insect damage was noted, mortality was attributed to defoliation. Fourteen of the 15 trees in this category died within 15 months of defoliation. Diameter growth of the surviving tree has been nonexistent since 1987 and the top died back during the 1987 growing season to the initial height of 2.74 meters. A lateral bud has assumed dominance.

Discussion

D.b.h. and height growth of the trees defoliated in April were generally reduced during the 1986 growing season (Weise et al. 1987). Approximately one-half of the year's volume growth was lost. All timings of defoliation have resulted in a growth loss that has not been regained. Recovery patterns of both species after defoliation were similar. D.b.h. and height growth of the January and April trees recovered the following growing season. Complete defoliation reduced d.b.h. from 12 to 57 percent and total height by 9 to 48 percent.

The mortality response to defoliation is of particular interest. Timing of defoliation appears to be critical. In both species, only trees completely defoliated in October died. All trees defoliated at all other timings and levels survived. Foliage removal just before dormancy may interrupt the storage of sugars which would be used during the winter months when the photosynthetic rate is reduced because of low temperatures. The trees may not have had sufficient resources to refoliate the following spring and thus died.

Trees severely scorched during other time periods often do die, but results reported here suggest that mortality associated with crown scorch from January through July results from stem, bud, or root damage--

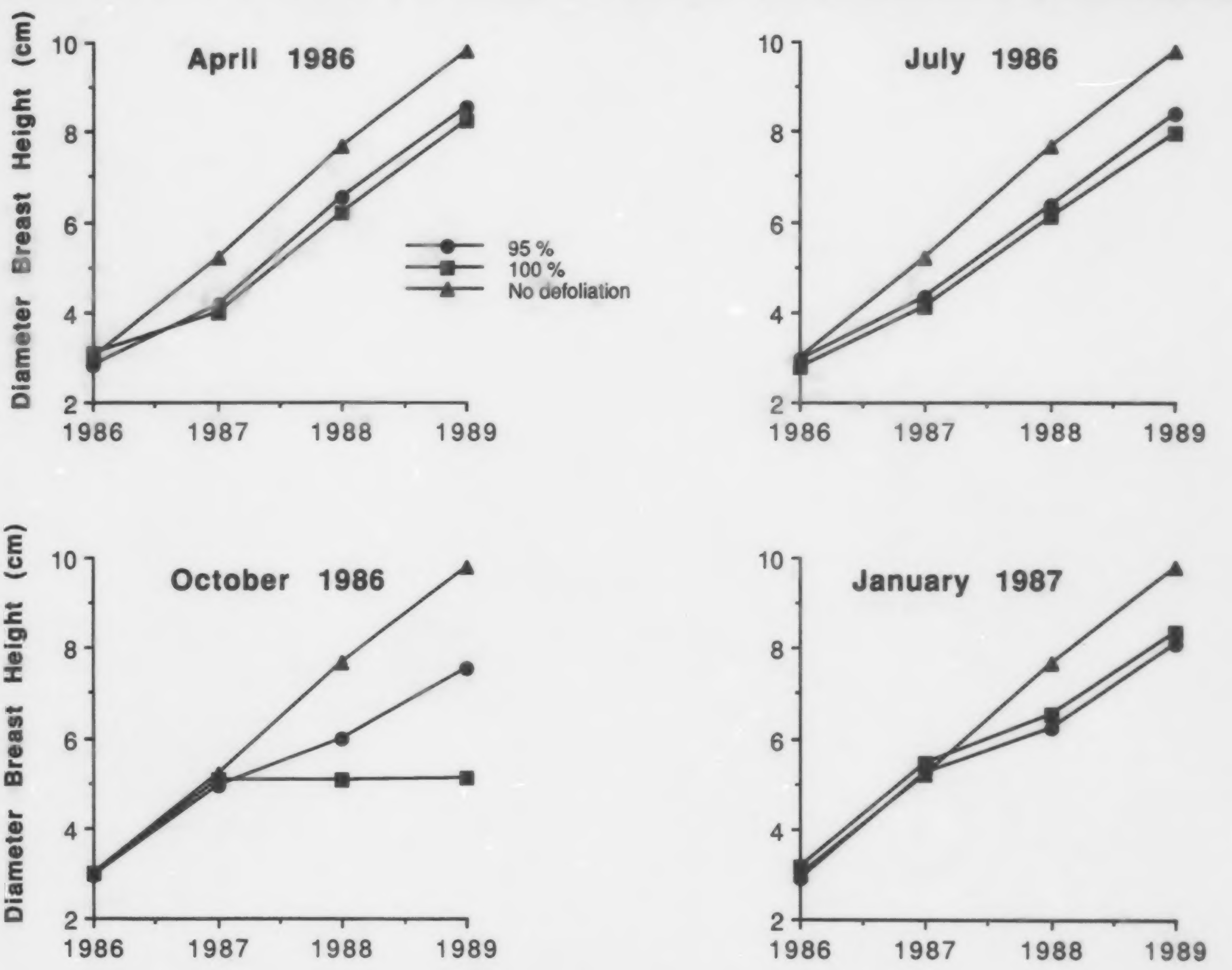


FIG 2. Diameter breast height response of 4-year-old plantation slash pine (Pinus elliottii Engelm.) to severe defoliation on a flatwoods site near Palatka, Florida.

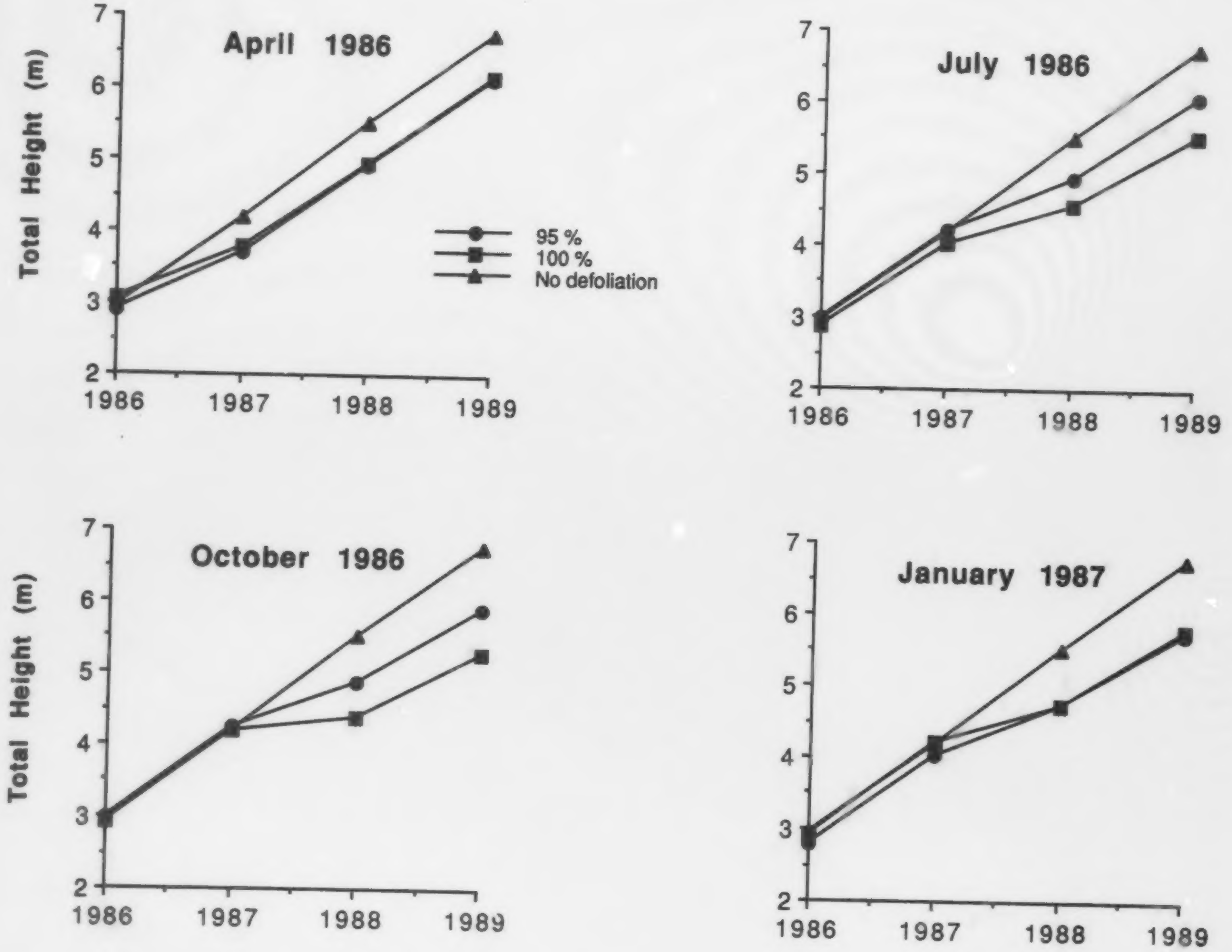


FIG 3. Total height response of 4-year-old plantation slash pine (Pinus eliottii Engelm.) to severe defoliation on a flatwoods site near Palatka, Florida.

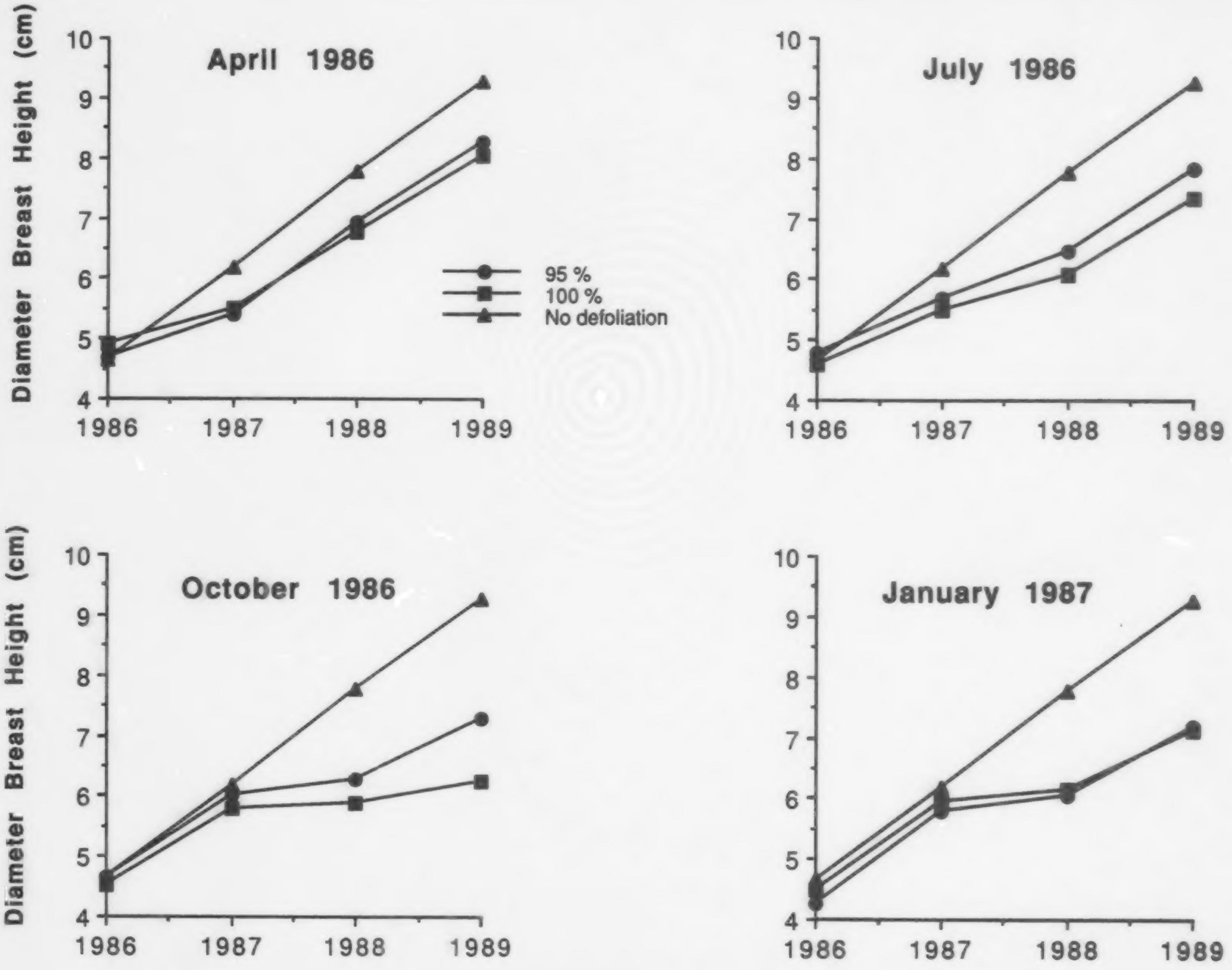


FIG 4. Diameter breast height response of 4-year-old plantation loblolly pine (Pinus taeda L) to severe defoliation on a coastal plain site near Bainbridge, Georgia.

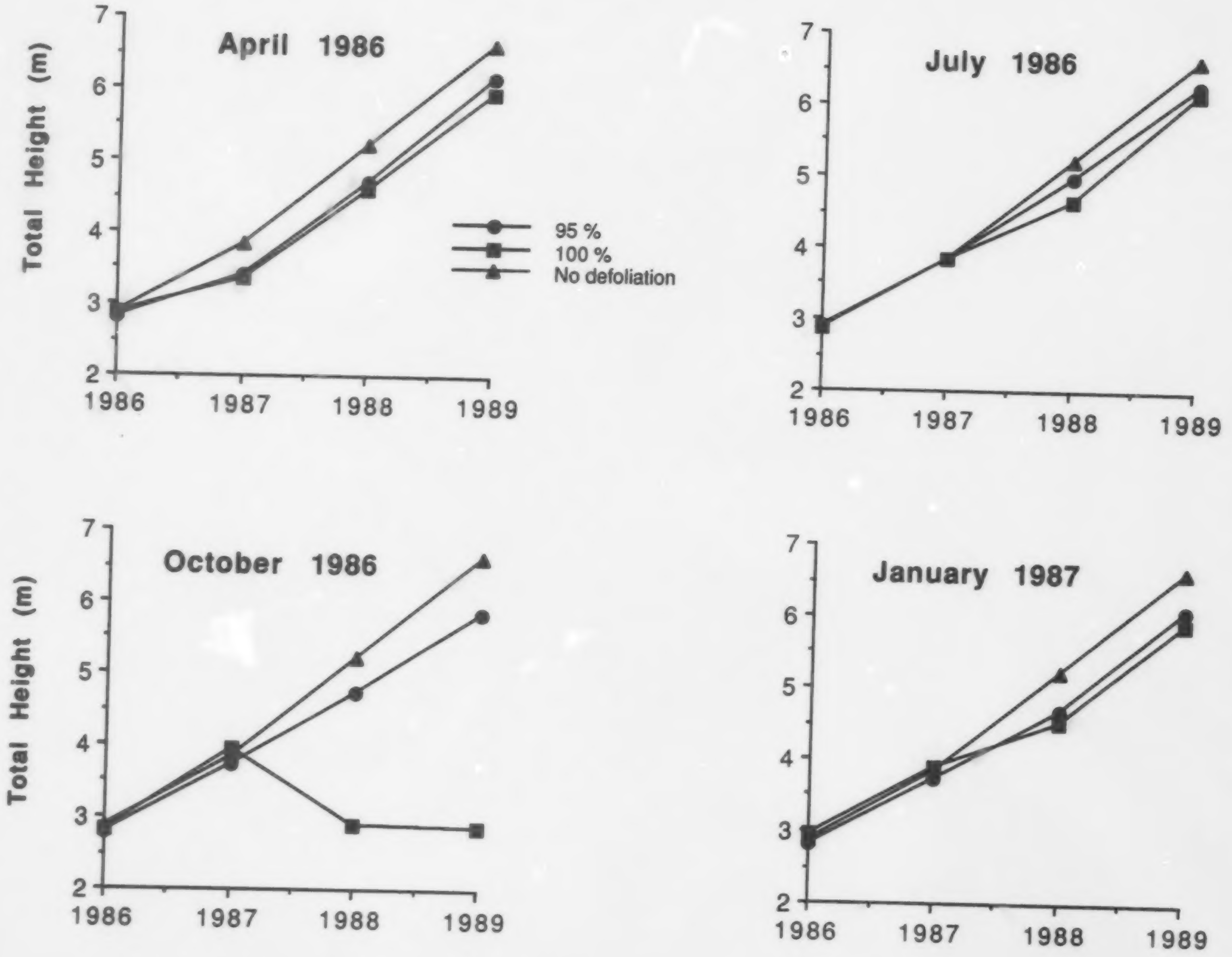


FIG 5. Total height response of 4-year-old plantation loblolly pine (Pinus taeda L) to severe defoliation on a coastal plain site near Bainbridge, Georgia.

not foliage loss. In a study involving more than 1,200 wildfire damaged loblolly pines less than 8 years old, Wade (1985) found only slight mortality occurred from crown scorch alone. However, as soon as some foliage was consumed, mortality increased significantly. Crown consumption implies bud damage which will cause tree mortality if extensive enough.

We did not evaluate the impact of bud damage on survival and growth of southern pines in this study. Intense wildfires can cause extensive stem damage but this is usually associated with crown consumption and thus bud injury. Johansen and Wade (1986) showed stem damage alone can kill small diameter southern pines. Once basal diameters exceed 5 cm, the bark becomes thick enough to protect the stem cambium. Root damage is a possibility, especially in older trees that can not replace heat-killed feeder roots as fast as rapidly growing younger trees. Thus we hypothesize that bud damage is the principal cause of death once trees have attained a diameter of several centimeters.

Waldrop and Van Lear (1984) examined the effects of prescribed fire on unthinned 17-year-old loblolly pine. The prescribed burns were conducted in June, August, or October 1979. Complete crown scorch (foliage and tips of branches scorched) occurred in the high intensity fires. They reported that "diameter growth of trees subjected to even high-intensity flames was not significantly affected in the year following burning." Our results contradict their statement.

All severe (> 66 percent) defoliation level/timing combinations resulted in a d.b.h. and height growth loss for slash and loblolly pine. Complete defoliations of 4-year-old loblolly pines resulted in d.b.h. growth reductions of 16, 18, and 48 percent for April, July, and October defoliations, respectively; slash pine d.b.h. growth reductions were 12, 20, and 30 percent. Growth was reduced within 12 months of defoliation. these growth losses are similar to those reported for older southern pines. Villarubia and Chambers (1978) documented a significant d.b.h. growth loss in completely scorched 20 year old loblolly pine in the growing season following an October 1976 prescribed fire. Johansen and Wade (1987) reported that complete scorch resulted in a 34 to 68 percent loss in d.b.h. growth of 25 year old plantation grown slash pine for the 2 year period after a January 1982 prescribed fire. Thus, although loblolly and slash pine can withstand complete defoliation during the winter, spring, and summer months, one should expect significant short-term growth loss. Johansen (1975) found the growth rate of severely crown damaged slash pine initially decreased and then increased until both slightly and severely damaged trees outgrew the undamaged control trees. This does not appear to be happening in our current study. We simulated the effects of fire, and thus the trees did not get the nutrient mineralization and understory control benefits accruing from an actual fire.

Conclusions

Partial and complete defoliation reduced d.b.h. and height growth of 4-year old loblolly and slash pines. Growth losses occurred within 12 months of defoliation. October defoliations had the greatest impact on growth--93 percent of completely defoliated loblolly pine died within 15 months and 40 percent of the completely defoliated slash pine died within 27 months. Winter, spring, and summer defoliations did not cause mortality.

Prescribed burning during the dormant season should not cause mortality -- provided only foliar scorching results. However, severe crown scorch may cause a d.b.h. and height growth loss of up to 50 percent. Care should be taken in planning and conducting prescribed burns in young southern pine stands in order to minimize the potential loss.

Acknowledgements

We would like to thank the Georgia Forestry Commission, International Paper Company, Union Camp Corporation, and Westvaco for their generous support of this study.

References

JOHANSEN, R.W. 1975. Prescribed burning may enhance growth of young slash pine. J. For. 73(3):148:149.

JOHANSEN, R.W. and D.D. WADE. 1986. An insight into thinning young slash pine stands with fire. P. 103-106 In D.R. Phillips, ed., Proc. Fourth Biennial South. Silvic. Res. Conf., Atlanta, Ga., Nov. 4-6, 1986, USDA For. Serv. Gen. Tech. SE-42, Southeastern For. Exp. Sta., Asheville, NC.

JOHANSEN, R.W. and D.D. WADE. 1987. Effects of crown scorch on survival and diameter growth of slash pines. South. J. Appl. Forest. 11(4):180-184.

KRAMER, P.J. 1943. Amount and duration of growth of various species of tree seedlings. Plant Physiol. 18:239-251.

VILLARUBIA, C.R. and J.L. CHAMBERS. 1978. Fire: its effects on growth and survival of loblolly pine, Pinus taeda L. Proc. La. Acad. Sci. 41:85-93.

WADE, E.E., and R.W. JOHANSEN. 1986. Effects of fire on southern pine: observations and recommendations. USDA For. Serv. Gen. Tech. Rep SE-41. Southeastern For. Exp. Sta., Asheville, NC.

WALDROP, T.A., and D.H. VAN LEAR. 1984. Effects of crown scorch on survival and growth of young loblolly pine. South J. Appl. Forest. 8(1):35-40.

WEISE, D.R., R.W. JOHANSEN, and D.D. WADE. 1987. Effects of spring defoliation on first-year growth of young loblolly and slash pines. USDA For. Serv. Res. Note SE-347, Southeastern For. exp. Sta., Asheville, NC.

Climate Change and Wildfire in Northern Coniferous Forests: Climate Change Scenarios

R.W. WEIN
University of Alberta
Edmonton, Alberta

Abstract

The study of past climates has established that there have been wide swings in climate trends and forest composition has responded. There is overwhelming evidence that climates are warming at present, but the rate of change requires refinement and the spatial dimensions of temperature and especially moisture are required for landscape management. Some climate change scenarios suggest that the northwestern part of Canada will become warmer and drier over the next 30 to 50 years. As climate changes, present forests will come under increasing levels of low moisture stress so that stands may die and thereby increase fuel loads. This could lead to more frequent, intense and severe fires. Fire suppression organizations already have highly sophisticated equipment and use a well-developed decision-making system. Fire management approaches will respond to a level that prevailing economic conditions will permit but the predicted extremes of climate will inevitably lead to fires and changed stand composition over large areas throughout northwest Canada.

Researchers are ill-prepared to predict forest changes with sufficient accuracy that changes in forest management can be justified. This is why research is now exploring how forest composition has changed (through dendrochronology and through pollen analysis) during past warm periods, how genetically and physiologically tree species tolerate moisture stress, how stand productivity and seedling establishment changes under increasing high temperature and drought stress.

Résumé

L'étude des conditions climatiques du passé a révélé que le climat avait largement oscillé et que la composition des peuplements forestiers s'était modifiée sous cette influence. Certains faits viennent indéniablement prouver que le climat se réchauffe à l'heure actuelle, mais la rapidité du changement exige des recherches plus approfondies et l'extension dans l'espace des régimes de température etnotamment d'humidité doit être connue pour permettre l'aménagement de la végétation.

Certains scénarios de changement climatique laissent entendre que la région nord-ouest du Canada se réchauffera et s'asséchera au cours de 30 à 50 prochaines années. A mesure que le climat se modifiera, les forêts actuelles seront soumises à un stress de plus en plus marqué causé par une faible humidité de sorte que les peuplements pourront en mourrir et ainsi accroître la biomasse de combustible. Il pourrait s'ensuivre des incendies beaucoup plus fréquents, intenses et graves. Les organismes chargés de la lutte contre les incendies disposent déjà d'un équipement très sophistiqué et utilisent des systèmes d'aide à la décision bien conçus. Les approches en gestion des incendies prévoieront des interventions à la mesure des conditions économiques del'époque, mais les extrêmes climatiques prévus causeront inévitablementdes incendies et entraîneront une modification de la composition des peuplements dans de vastes régions de l'ensemble du nord-ouest du Canada.

Les chercheurs ne sont pas en mesure de prédire les modifications de la forêt avec suffisamment de précision pour justifier des changements à l'aménagement forestier. C'est la raison pour laquelle des chercheurs étudient actuellement les modifications de la composition des peuplements (grâce à la dendrochronologie et à l'analyse du pollen) qui se sont produites lors des périodes antérieures de réchauffement, les mécanismes génétiques et physiologiques de tolérance au stress hygriquede différentes essences et les modifications de la productivité des peuplements et de l'implantation des semis face à un accroissement de la température et de la sécheresse.

Climate Change Update

J.B. HARRINGTON
Canadian Forestry Service
Petawawa National Forestry Institute
Chalk River, Ontario

Abstract

A recent review of the causes of climatic change (Harrington, Can. J. For. Res., 17, 1313-1339) was made possible by the piecing together of hundreds of clues provided by research in all of the geophysical sciences and by the numerical modeling of the atmosphere, lithosphere, hydrosphere, cryosphere and biosphere. Progress in these fields over the past year has strengthened the cometary theory of mass extinctions, strengthened the theory of orbital influences on glaciation, strengthened theories relating climate to variations in solar luminosity, weakened theories relating climate change to volcanism, and greatly increased the perceived influence of the biosphere. The biggest surprise of the past year was the confirmation that the Antarctic ozone hole is man-caused. The most notable scientific advance was the analysis of the Vostok ice core by a Russian-French team. The greatest mystery continues to be the role of ocean circulation in causing or modulating climate change.

Résumé

Un examen récent des causes des modifications du climat (Harrington, Journ. can. rech. for., 17. 1313-1339) a pu être effectué grâce au rassemblement de centaines d'indices contenues dans les travaux de chercheurs de l'ensemble des sciences géophysiques et grâce à la modélisation numérique de l'atmosphère, de la lithospère, de l'hydrosphère, de la cryosphère et de la biosphère. Les progrès accomplis dansces domaines au cours des dernières années ont renforcé la théorie de l'extinction de la masse des comètes, la théorie de l'influence de l'orbite sur la glaciation et les théories établissant un lien entre leclimat et les variations de la luminosité du soleil, ont affaiblis les théories corrélant les modifications du climat à l'activité volcanique et ont fait énormément prendre conscience de l'influence de la biosphère. L'an dernier, notre plus grande surprise a été la confirmation que l'homme était responsable du trou observé dans la couche d'ozone au-dessus de l'Antarctique. La poussée scientifique la plus remarquablea été l'analyse du noyau de glace de Vostok effectuée par une équipe franco-russe. Le rôle de la circulation océanique dans le déclenchementou la modulation des modifications du climat reste toujours le plus grand mystère.

Changing Climatic Resources for the Western Canadian Boreal Forest

E.E. WHEATON AND J.P. THORPE
Saskatchewan Research Council
Saskatoon, Saskatchewan

Abstract

The structure and function of the boreal forest ecosystem are more clearly dependent on climate than many other ecosystems. Climate and its influences on the ecosystem are dynamic. The climate has changed in the past and will continue to change into the future. The climatic change of increasing concern is based on the documented increase in the atmospheric concentrations of the "greenhouse gases". Climatic change scenarios based on the results from two General Circulation Models were used to explore the effects of a $2xCO_2$ climate on the boreal forest of Western Canada. The implications of the enhanced greenhouse effect for the boreal forest are very serious because of the combination of the forest's sensitivity to climate and the fact that greatest temperature increases are projected for the higher latitudes the location of the boreal forest. Methods for climatic change impact assessment are presented, including the design and classification of climatic change scenarios and the use of a system analysis approach. The impacts of climatic change on the climatic resources for the forest, including changes in thermal and moisture resources as well as biomass potential are examined. Preliminary assessments indicate considerable changes. Some recommendations for future study are made.

Résumé

Il est clair que la structure et la fonction de l'écosystème de la forêt boréale dépend d'avantage du climat que bon nombre d'autres écosystèmes. Le climat et son influence sur l'écosystème sont dynamiques. Le climat s'est modifié au cours des siècles et continuera de le faire. Le changement climatique de plus en plus préoccupant est provoqué par l'augmentation bien connue des concentrations atmosphériques des "gaz responsables de l'effet de serre". Des scénarios dechangement climatique basés sur les résultats de deux modèles de circulation générale ont été utilisés pour explorer les effets sur la forêt boréale de l'Ouest du Canada d'un climat à teneur deux fois plus élevée en CO_2. Les incidences d'un effet de serre plus marqué sur la forêt boréale sont très graves parce que la vulnérabilité de la forêt au climat se conjugue au fait que de plus fortes augmentations des températures sont prévues à ces latitudes élevées, là où se trouve la forêt boréale. Des méthodes pour évaluer l'impact d'un changement climatique sont présentées, y compris la conception et la classification de scénarios de changement climatique et le recours à une approche d'analyse du système. L'impact du changement climatique sur les ressources climatiques pour la forêt, y compris des modifications des ressources thermiques et hygriques ainsi que du potentiel de la biomasse, est examiné. Des évaluations préliminaires indiquent que des changements considérables se produiront. Certaines recommandations d'études à entreprendre sont formulées.

Introduction and Objectives

The structure and function of the boreal forest ecosystem are more clearly dependent on climate than many other ecosystems. Climate and its influences on the ecosystem are dynamic. The climate has changed in the past and will continue to change into the future. The climatic change of increasing concern is based on the documented increase in atmospheric concentrations of the "greenhouse gases".

The implications of the enhanced greenhouse effect for the boreal forest are very serious because of the combination of the forest's sensitivity to climate and the fact that the greatest temperature increases are projected for the higher latitudes which is the locationof the circumpolar boreal forest. A recent U.S. Environmental Protection Agency study on the impacts of climate change reports that natural ecosystems will suffer the most damage as a result of an enhanced greenhouse effect. Smith, a co-editor, presents the most surprising finding as that the forests are extremely sensitive to temperature changes. Even a warming of 1°C could cause the southern borders of forests throughout the country to move northward (Horgan 1989). This sensitivity is apparent when one examines graphs of the mean annual temperature of boreal forest subregions over time such as those presented by Singh and Powell (1986). These relationships indicate that the forest-grassland transition and the predominately forest subregion in western Canada is only separated by about 2°C in mean annual temperature. So an increase of even 2°C in mean annual temperature that

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

persisted over an extended period could result in a mismatch of climate and ecosystem. Singh and Powell (1986) also found that all three subregions of this study area showed significant ($P<0.05$) warming trends during 1872-1981 and the predominantly forest and the forest-grassland subregion trends were highly significant ($P<0.01$).

The primary purpose of this work is to discuss methodologies for climatic change impact assessment and to show preliminary results as described in Wheaton et al. (1987). Potential impacts of climatic change on the climatic resources for the forest are examined. Preliminary assessments indicate considerable potential changes. Some recommendations for future study are made.

Methodology

It is very important to apply the most useful methodologies for the assessment of the impacts of climatic change and variations on ecosystems. Much more work is required to define and verify the basic relationships between climate and ecosystems even without a change in climate. The need for the best modelling efforts becomes essential with an increasing probability of changes in climate. Several methodologies, including the design and classification of climatic change scenarios, impact models, and a system analysis approach are examined.

CLIMATIC CHANGE SCENARIO ANALYSIS

A climatic change scenario has been defined as a description of the spatial and seasonal behaviour of temperature, precipitation and other important meteorological variables in an altered climatic state (Santer 1985). Climatic change scenarios of various types have been used. Wheaton has designed a classification to characterize these as follows:1) historical and areal analogues, 2) synthetic, 3) General Circulation Model (GCM) derived and 4) hybrid climatic change scenarios (Maybank et al. 1987). Descriptions of these types as well as their advantages and disadvantages are provided in Maybank et al. (1987). Paleoanalogues may also be useful as climate change scenarios.

The GCM derived hybrid climatic change scenarios were selected for similar use in Wheaton et al. (1987). The GCM results are from experiments undertaken by the Goddard Institute for Space Studies (GISS) and the Geophysical Fluid Dynamics Laboratory (GFDL). The scenarios based on GISS results have grid point sizes of 4° latitude by 5° longitude and the gridpoint sizes for the GFDL based scenarios have grid sizes of approximately 4.5° latitude by 7.5° longitude. Historical climatic data and the GCM results were used to generate the hybrid climatic change scenarios using methodology developed by Williams et al. (1988).

Four gridpoints for each of GISS based and GFDL based scenarios were selected to represent the three main forest zones for some of the analyses, especially those requiring much data. Five gridpoints are in the predominately forest zone and two are in the forest-grassland transition zone and one is in the forest tundra transition zone. These points are assumed representative of the grid area and thus of a large portion of a forest zone and not necessarily of that point. The results of all of the impact models should be provided for all the available gridpoint locations in future studies once the impact model is decided to be appropriate.

Climatic characteristics of the temperature and precipitation of the scenarios are a foundation for examining the results of the climatic impact models that are based on temperature and precipitation data. These climatic characteristics are displayed through time and space and described in Wheaton et al. (1987).

Simulated Zonation and Productivity of the Boreal Forest

Several climatic impact models were used for the climatic change impact assessment. The modelled results include growing degree-days, precipitation effectiveness, ecoclimatic zonation, and the climatic index of biomass potential.

Growing degree-days (GDD) are selected because of their long history of characterizing the thermal climate for vegetation, both in Canada and internationally. GDD are indicative of both growing season length and temperature. They have been used in another climatic change impact on forestry study (Kauppi and Posch 1988) for similar reasons.

GDD results indicate increases of 13 to 14% above normal for the gridpoints examined (Table 1). The increases are largest for the most northerly points and smallest for the southern points.

The precipitation effectiveness index (I) of Thornthwaite (1931), also calculated from a relatively simple model, uses available data and is suitable for displaying spatial patterns. It is a function of both temperature and precipitation, in which evaporation is expressed in terms of temperature and it was derived from empirical data. An advantage of this index for our purposes is that it was designed for a climatic classification in relation to vegetation and soil classifications and is useful for characterizing spatial patterns of large areas. Newer versions of this model, with modifications to improve its relevance, should be applied and examined in future work.

Differences between the GFDL scenarios are illustrated by the I results (Table 1). The GFDL1 scenario, with both temperature and precipitation increases, shows increased I above the mean up to 17%, except for the most northern location. The GFDL2 scenario, which uses the increases in temperature and normal precipitation, shows consistent decreases of 7 to 9% for all locations.

The climatic index of biomass potential (Turc and Lecerf 1972), CA, reflects both thermal and moisture resources and is computed by summing the 12 monthly

TABLE 1. Impact model results implied by the GFDL based climatic change scenarios. Source: after Wheaton et al. 1987.

		Location (64° 24'N 120° 00'W)			Location (55° 30'N 105° 00'W)	
	HIST[a]	GFDL1	GFDL2[b]	HIST[a]	GFDL1	GFDL2[b]
	(1951-80)	(2xCO_2TP)[c]	(2xCO_2T)	(1951-80)	(2xCO_2TP)[c]	(2xCO_2T)
Growing Degree-days (GDD)	887	+40%	+40%	1111	+31%	+31%
Precipitation Effectiveness Index (I)	33.3	-6%	8%	50.0	+16%	-7%
Biomass Potential (CA)	8.6	+22%	+13%	13.6	+39%	+5%
Forest Zonation	Subartic	Parkland	Parkland	Boreal	Boreal-Temperate	Boreal-Temperate

		Location G (59° 54'N 120° 00'W)			Location H (51° 06'N 112° 30'W)	
	HIST[a]	GFDL1	GFDL2[b]	HIST[a]	GFDL1	GFDL2[b]
	1951-80)	(2xCO_2TP)[c]	(2xCO_2T)	(1951-80)	(2xCO_2TP)[c]	(2xCO_2T)
Growing Degree-days (GDD)	1140	+34%	+34%	1521	+13%	+13%
Precipitation Effectiveness Index (I)	42.3	+6%	-9%	33.3	+17%	-8%
Biomass Potential (CA)	12.6	+46%	+13%	7.7	+118%	+44%
Forest Zonation	Boreal	Parkland	Parkland	Grassland	Grassland	Grassland

Note: Values in percent are the percentage increases or decreases in relation to the mean values for the 1951 to 1980 historical standard period (HIST).

[a] the mean values for the 1951 to 1980 historical standard period.

[b] GFDL2 scenario uses normal precipitation means.

[c] T and P stand for temperature and precipitation.

products of heliothermic and moisture factors. The heliothermic factor (HT) includes both temperature and solar parameters. The soil moisture factor (Fs) is computed using precipitation and temperature in a climatic soil moisture budgeting procedure.

Thus CA reflects the length of the growing season and the amount of heat and moisture available to plants during the season. It is indicative not only of the agricultural potential of the climate, but also of the potential for biomass productivity in general, including hay and forest productivity, for examples (Turc and Lecerf 1972). Another advantage of this model is that it can be used to explore changes in biomass in general and is not limited to one vegetation type. Considering that climatic change may be accompanied by a shift in vegetation zones, this capability is very appropriate.

The term biomass productivity is used here as equivalent to total harvestable dry matter, which would include the weight, after drying, of all plant material. Turc and Lecerf (1972) suggest that each unit of CA is equivalent to dry matter production of about 0.6 tonnes per hectare. This value can then be adjusted by a harvest index in order to indicate the harvestable timber amounts, for example.

Monthly and annual values of CA, Fs and HT were computed for a few gridpoints in the study area for several climatic change scenarios and for the normal climatic data. The required data include monthly averages of daily mean temperature, daily minimum temperature, monthly total precipitation, average monthly global solar radiation, and median monthly daylength. The solar radiation data were not adjusted, so the assumption is that the solar radiation remains the same. The mathematical basis of CA is explained in detail in Williams (1985) and Williams et al. (1988).

Examples of changes in potential biomass productivity range from increases as low as 5% in the predominately forest subregion for GFDL2 to 118% greater than normal at the southern location for GFDL1(Table 1).

The arctic and boreal zones show a clear zonation from north to south: from arctic tundra, through a subarctic transition zone of widely spaced trees, to the closed boreal forest, and finally to more temperate vegetation types. This zonation closely parallels the isolines of rising temperature but is perpendicular to the east-west gradient in precipitation, and the northern and southern boundaries of the boreal zone have been correlated with values of annual net radiation, frost-free period, July mean temperatures, potential evapotranspiration, and growing degree-days (Hare and Ritchie 1972, Tuhkanen 1980, Kauppi and Posch 1985, 1988). These climatic correlations are summarized by Thorpe in Wheaton et al. (1987).

A simple approach, therefore, to projecting the impact of climatic change is to shift the thermal isolines corresponding to the boundaries. Kauppi and Posch (1985) considered the boreal zone to be bounded by values of 600 degree-days above 5°C in the north and 1300 degree-days in the south. Simulated warming with doubling of CO_2 produces a worldwide northward displacement of this zone by 500 to 1000 km. According to the climatic change scenarios used in Wheaton et al. (1987), the northward shifts in these isolines for western Canada would range from 100 to 700 km for the northern boundary, and from 250 to 900 km for the southern boundary.

Closer examination of this zonation shows that the correspondence to thermal isolines is clearest in humid regions such as Europe and eastern North America, where the boreal forest grades southward into temperate deciduous forest. In the Canadian prairies, the boreal forest is "dry subhumid" in most portions except for north-east Saskatchewan and northern Manitoba which are "moist subhumid" (Richards and Fung 1969). The southern edge is a transition zone of aspen parkland, giving way southward to semiarid grassland. The southern boundary here does not precisely parallel the thermal isolines; rather, it occurs at relatively cooler locations in Alberta, where precipitation is lower, and warmer locations in moister Manitoba. Thus it appears that moisture availability (the balance between precipitation inputs and evaporative outputs) controls this transition from forest to grassland.

The model shown in Figure 1 approximates this zonation. The basic thermal zonation is modelled by values of growing degree-days obtained by comparing the vegetation map (Rowe 1972) with climatic maps (Environment Canada 1984). The diagonal lines representing the semiarid transition were calculated by locating 19 stations along the parkland/boreal boundary, and 22 stations along the grassland/parkland boundary. Growing degree-days and annual precipitation of the stations (Environment Canada 1982) were related by a linear regression for each boundary. Thus the regression lines represent the increasing temperature sum required to produce the vegetation boundary as precipitation increases.

If we apply this model to four grid points (Table 1), we see that present climatic data assign these points to the correct present vegetation zones. Using simulated climatic data from the GFDL1 and GFDL2 scenarios, the model predicts that the subarctic and boreal points at 120° W will become aspen parkland, while the more easterly boreal point will become boreal-temperate forest. Incorporating the role of moisture variation in zonation results in a more refined prediction of the impact of climatic change. Instead of the simple northward shift of zones predicted by Kauppi and Posch (1985), it appears that aspen parkland will extend northward in the drier western part, and boreal-temperate forest in the more humid eastern part of the prairie boreal zone.

All models of this sort must be interpreted with caution. They assume that vegetation zonation is in equilibrium with climate, both in the present situation used for calibration, and in the future simulated situation. More research is needed to determine the extent to which present zonation is in equilibrium. Probably more importantly, future changes will be slowed by the long lifespans of presently established trees, and in some cases by the short transport distances of propagules of invading species. Even if climate does change as dramatically as projected for the next 50 years, it may take centuries for vegetation change to catch up to the new climatic potentials. This may not hold true if depletion factors such as fire, insects and diseases respond positively to climatic warming and act as agents of change. The relation of these depletion factors and climatic change and variability should be further explored.

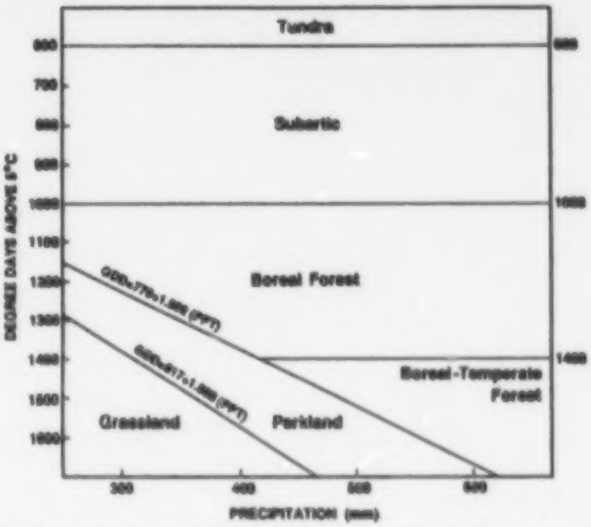


FIG. 1. The Boreal Zonation Model - Criteria for assigning stations to vegetation zones. Source: Wheaton et al. 1987.

The recommendations suggested herein and many others are briefly explained and listed in Wheaton et al. (1987). Woodman and Furiness (1988) also emphasize the need for improved climatic scenarios on a regional basis and improved knowledge of the relation between forest ecosystems and climate. Wheaton et al. (1987), Woodman and Furiness (1988) and others point out the need for much further information from more detailed analyses and that the need for new research is obvious. The most important questions may be those that have yet to be asked.

A systems analysis approach can provide a research framework for creating, developing, testing and improving conceptual and mathematical sets of interactive models. Such an approach could also be used to explore the impact of policy decisions on the resilience of the ecosystems and the rate of change. A preliminary climatic change-forest-economics-policy system diagram was developed by Wheaton et al. (1987) (Figure 2). This approach is especially effective for

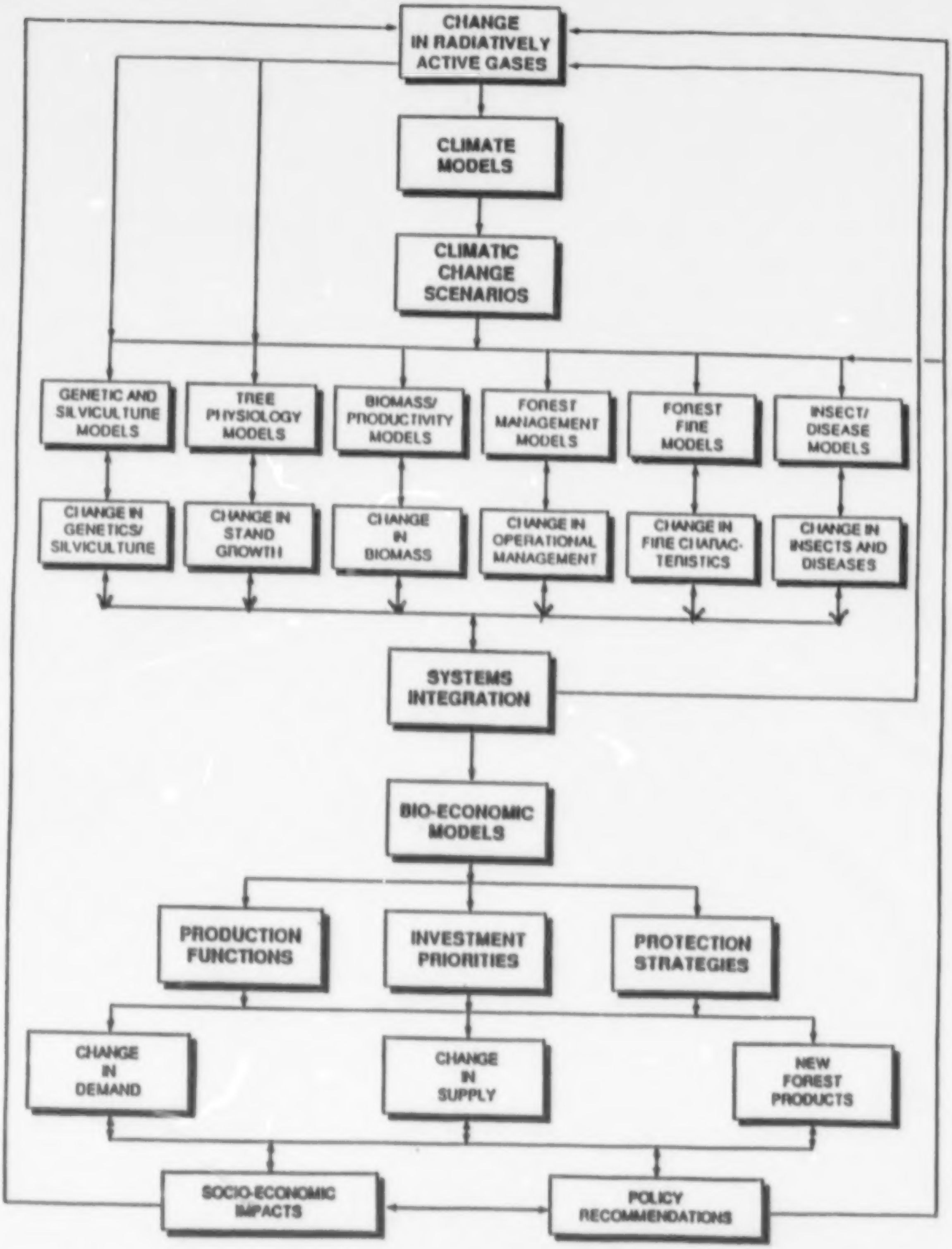

CHANGE IN RADIATIVELY ACTIVE GASES
CLIMATE MODELS
CLIMATIC CHANGE SCENARIOS
GENETIC AND SILVICULTURE MODELS
TREE PHYSIOLOGY MODELS
BIOMASS/ PRODUCTIVITY MODELS
FOREST MANAGEMENT MODELS
FOREST FIRE MODELS
INSECT/ DISEASE MODELS
CHANGE IN GENETICS/ SILVICULTURE
CHANGE IN STAND GROWTH
CHANGE IN BIOMASS
CHANGE IN OPERATIONAL MANAGEMENT
CHANGE IN FIRE CHARAC-TERISTICS
CHANGE IN INSECTS AND DISEASES
SYSTEMS INTEGRATION
BIO-ECONOMIC MODELS
PRODUCTION FUNCTIONS
INVESTMENT PRIORITIES
PROTECTION STRATEGIES
CHANGE IN DEMAND
CHANGE IN SUPPLY
NEW FOREST PRODUCTS
SOCIO-ECONOMIC IMPACTS
POLICY RECOMMENDATIONS

FIG. 2. System Diagram Illustrating Climatic Change/Forest/Economics/Policy Interactions.

interdisciplinary studies such as climatic change impact assessment.

References

ENVIRONMENT CANADA, ATMOSPHERIC ENVIRONMENT SERVICE (AES). 1982. Canadian climatic normals, 1951-1980. AES, Environment Canada, Downsview, Ontario.

ENVIRONMENT CANADA, ATMOSPHERIC ENVIRONMENT SERVICE (AES). 1984. Climatic atlas Canada, Map Series 1, Temperature and degree days. AES, Environment Canada, Downsview, Ontario.

HARE, F.K., AND J.C. RITCHIE. 1972. The boreal bioclimates. Geographical Review 62:333-365.

HORGAN, J. 1989. Greenhouse America - A global warming may destroy U.S. forests and wetlands. Scientific American 260(1):20-21.

KAUPPI, P., AND M. POSCH. 1985. Sensitivity of boreal forests to possible climatic warming. Climatic Change 7(1):45-54.

KAUPPI, P., AND M. POSCH. 1988. A case study of the effects of CO2-induced climatic warming on forest growth and the forest sector: A. Productivity reactions of northern boreal forests. In Parry et al. op. cit., Part I:183-195.

MAYBANK, J., E.E. WHEATON, AND G.C. VAN KOOTEN. 1987. Tree growth responses to changes in the physical and chemical climate and methods to assess economic consequences. Paper presented at the International Union of Forest Research Organizations Workshop, Vancouver, July 27-29, 1987. Saskatchewan Research Council, Saskatoon, Saskatchewan. Saskatchewan Research Council Publication No. E-906-17-D-87.

PARRY, M.L., T.R. CARTER, AND N.T. KONIJN, eds. 1988. The Impact of Climatic Variations on Agriculture, Vol 1: Assessments in cool temperate and cold regions. Kluwer Academic Publishers, Dordrecht. 876 pp.

RICHARDS, J.H., AND K.I. FUNG. 1969. Atlas of Saskatchewan. University of Saskatchewan, Saskatoon.

ROWE, J.S. 1972. Forest regions of Canada. Canadian Forestry Service Pub. No. 1300. 172 pp and map.

SANTER, B. 1985. The use of General Circulation Models in climate impact assessment - A preliminary study of the impacts of a CO2-induced climatic change on Western European agriculture. Climatic Change 7:71-93.

SING, T., AND J. POWELL. 1986. Climatic variation and trends in the boreal forest region of western Canada. Climatic Change. 8:267-278.

THORNTHWAITE, C.W. 1931. The climates of North America according to a new classification. Geog. Rev. 21:633-655.

TUHKANEN, S. 1980. Climatic parameters and indices in plant geography. Acta Phytogeographica suecic 67. 110 pp.

TURC, L., AND H. LECERF. 1972. Indice climatique de potentialite agricole. Science du Sol 2:81-102.

WHEATON, E.E., T. SINGH, R. DEMPSTER, K.O. HIGGINBOTHAM, J.P. THORPE, AND G.C. VAN KOOTEN, WITH J.S. TAYLOR. 1987. An exploration and assessment of the implications of climatic change for the boreal forest and forestry economics of the Prairie provinces and Northwest Territories: Phase One. Saskatchewan Research Council Publication No. E-906-36-B-87, Saskatoon, Saskatchewan. 282 pp.

WILLIAMS, G.D.V. 1985. Estimated bioresource sensitivity to climatic change in Alberta, Canada. Climatic Change 7:55 69.

WILLIAMS, G.D.V., R.A. FAUTLY, K.H. JONES, R.B. STEWART, AND E.E. WHEATON. 1988. Estimating effects of climatic change on agriculture in Saskatchewan, Canada. In Parry et al. op. cit., Part II:221379.

WOODMAN, J.N., AND C.S. FURINESS. 1988. Potential effects of climate change on U.S. forests: case studies of California and the southeast. Report written for the U.S. EPA as basis for a report to U.S.Congress. N. Carolina State University, Raleigh, N.C. 36 pp.

Climate Change and Forest Fires in Ontario

R. B. STREET
Atmospheric Environment Service, Environment Canada
Downsview, Ontario

Abstract

The intrinsic link between fire and climate suggests that changes in climate induced by increasing concentrations of "greenhouse gases" will have a significant impact on forest fire severity. This paper examines this impact in terms of probable changes in the length and severity index of the Canadian Fire Weather Index. Monthly historical data of average temperatures, precipitation totals and fire severity indicies for stations within each of the administrative regions of Ontario are used to define statistical (second degree orthogonal polynomial technique) relationships for each region. These relationships are then used, along with the results of two climate change scenarios, to define the fire severity indices for each region and each month under the modeled climatic conditions.

The general trend of the analysis indicates that in all regions of Ontario the forest fire season under the proposed climatic conditions will be longer, starting during the month of April and continuing into the month of October. It was also evident that the fire seasons will generally be more severe than those under the current climatic normals. In addition to a general increase in overall severity, the analysis suggests that there will also be a shift in the timing of the most severe portion of the fire season. Traditionally the months of May, June and July have been the most severe, however, under the modelled climate of the two change scenarios, the most severe portions of the fire season will shift to later in the season, typically July, August and September. There was also an indication that in some regions, particularly northwestern Ontario, a bimodal fire season is probable. In these situations, peak periods were identified during late spring followed by a second period during late summer.

Résumé

Le lien intrinsèque entre le feu et le climat permet de supposer que les modifications du climat provoquées par l'accroissement des concentrations des "gaz responsables de l'effet de serre" auront un impact important sur la gravité des incendies de forêt. Le présent article se penche sur les modifications probables de la durée et de la gravité de la saison des feux dans la province canadienne de l'Ontario à la suite des changements climatiques tels que définis par des augmentations de la teneur en CO_2 de l'atmosphère. La relation entre le feu et le climat est établie à l'aide de la cote numérique de gravité des incendie de l'Indice Forêt-Météo canadien. Des données mensuelles historiques des températures moyennes, du total des précipitations et des cotes numériques de gravité des stations de chacune des régions administratives de l'Ontario ont été utilisées pour définir des relations statistiques pour chaque région (technique polynomiale orthogonale de second degré). Ces relations sont ensuite utilisées de concert avec les résultats de deux scénarios de changement climatique pour définir des indices de gravité des incendies pour chaque région et pour chaque mois du scénario de conditions climatiques modélisées. La tendance générale de l'analyse révèle que la saison des feux de forêt de toutes les régions de l'Ontario, dans les conditions climatiques modélisées, sera plus longue, débutant en avril et se poursuivant jusqu'au cours du mois d'octobre. Il était également évident que la saison des feux serait également plus grave que celles prévalant sous nos régimes climatiques actuels. L'analyse laisse également supposer, outre une augmentation générale de la gravité de l'ensemble des incendies, une modification de la période pendant laquelle surviendra la partie la plus intense de la saison des feux. Les mois de mai, juin et juillet ont toujours été les mois les plus cruciaux; toutefois, avec les deux scénarios de changement climatique, la période critique de la saison des feux viendra plus tard, généralement en juillet, août et septembre. Certains résultats nous portent également à croire que certaines régions, notamment le nord-ouest de l'Ontario, pourraient connaître une saison des feux à deux volets, la première période cruciale survenant à la fin du printemps et la seconde à la fin de l'été.

Introduction

Forest fires have an overwhelming impact on the social and economic status and development of Ontario particularly in the boreal forest regions. This sensitivity is readily apparent even to the casual observer. Periods of extreme forest fire activity occur frequently and can have wide ranging impacts. The loss of timber and property, the potential for loss of life (both human and animal), the possibility of evacuation of people (as was the case in September 1984) and the cost of mobilizing and maintaining a fire fighting force are some of these impacts.

Tremendous fluctuations from year to year in both fire occurrence and area burned are common throughout Ontario. For example, during the period 1970 to

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

1980 fire numbers in northwestern Ontario varied by a factor of 10 from a low of 200 fires in 1978 to a high of more than 2100 fires in 1976. The annual area burned during this same 11 year period varied from a low of approximately 2600 hectares in 1978 to a high of more than 550,000 hectares in 1980. The severity of a particular fire season and therefore the number of fires and area burned is determined by the fire environment which in turn is a composite of the status of the fuel, weather and topography of the area. Weather is the most variable of these factors and the impact of changes in the weather (e.g. from a period that is relatively wet to one that is dry or vice versa) are well documented in the annals of forest fires in Ontario as well as throughout the world.

Recent climate research has suggested that the enhanced levels of atmospheric CO_2 associated with the combustion of fossil fuels and the reduction of forest biomass and soil organic matter will alter the global climate. These changes in climate are expected to be significant especially in the northern latitudes of Ontario. The suggested changes in climate are of particular concern to the forest fire community because of its sensitivity to climate. Any change in climate or climate variability has the potential to significantly alter the spatial and temporal distribution of forest fires.

It is my purpose in this paper to address the question of the potential impact of proposed climate change scenarios on the severity of the forest fire season in Ontario. For this analysis the climate change scenarios will be restricted to double the current level of CO_2 which, in terms of time, is equal to about one generation of a managed forest (Pollard 1985).

The fire severity index first developed by Williams (1959) and later updated by Van Wagner (1970) can be used as a means of evaluating the relative severity of the forest fire season in Ontario. This severity index is normally used in conjunction with the Canadian Fire Weather Index (FWI). These severity rating index values alone with the coincident daily climate values are readily available for the forested regions of Ontario. The analysis is undertaken on a regional and monthly basis during the fire season. Appropriate monthly values of temperature and precipitation are determined for each region. The relationship between these climate values and the regional monthly severity rating index (RMSRI) are then calculated using a second degree orthogonal polynomial technique (Dixon 1969). This relationship and the new regional climate (temperature and precipitation) determined from the climate change scenarios are then used to calculate the changed climate RMSRI values.

The analysis indicated that the fire seasons in Ontario under the influence of the proposed climate change scenarios will on average be longer and generally more severe that those suggested by the normal climate of the period 1963-1983.

Analysis Procedures

Two data sets form the basis of this analysis. The first of these data sets was obtained from the Great Lakes Forest Research Center of the Canadian Forestry Service. It is composed of daily weather observations (temperature, relative humidity, wind speed and the amount of rain (if any) during the past 24 hours) taken at local solar noon, the derived FWI component values and the daily severity rating index (DSRI). These observations and derived values are for the 21 year period from 1963-1983 and include values for all the available fire weather stations active during this period.

The second data set consists of monthly values of changes in the mean monthly temperature and the total monthly precipitation suggested by two climate change scenarios, Scenario A-2 and Scenario B (Hengeveld and Street 1985). These values were in the form of changes in temperature (degrees Celsius) and percent change in precipitation.

The distribution of the daily climate and DSRI values and the relationships between their variables were determined for the purpose of identifying any possible limitations to the type of statistical analysis that could be performed and possible erroneous data.

The fact that a simple relationship does not exist between the temperature, precipitation (values available from the historical data set) and the severity rating index (both on a day by day and monthly basis) requires that an analysis procedure other than simple or multiple regression analysis be used. It was decided that a second degree orthogonal polynomial technique (Dixon 1969) would be used to develop the relationships between the three variables. This technique defines a surface using the available data with temperature and precipitation as the independent variables and RMSRI as the dependent variable. The defined surface is then used to calculate values of RMSRI using other values of temperature and precipitation within the limits of the surface.

The climate change scenario data exists in a grid point format. The two scenarios used in this analysis (Scenario A-2 and Scenario B) have different grid point locations (Figure 1, Ontario Ministry of Natural Resources Regions). To calculate regional temperature change and percent precipitation changes from these grid point values, it is necessary to first weight the grid contributions to each regional value. This is accomplished by using an area weighing procedure. The fractional amount of each grid that is within each region is determined for both grid systems. On the basis of these weighted values, regional values of temperature and precipitation change are calculated for the two climate change scenarios for each month.

A further modification of the climate change data is necessary in order to reflect the fact that the climate data used to calculate the DSRI values consists of local solar noon temperatures rather than daily mean temperatures. Instead of suggesting that the temperature distribution during the day would remain the same under the climate change scenarios the temperature is

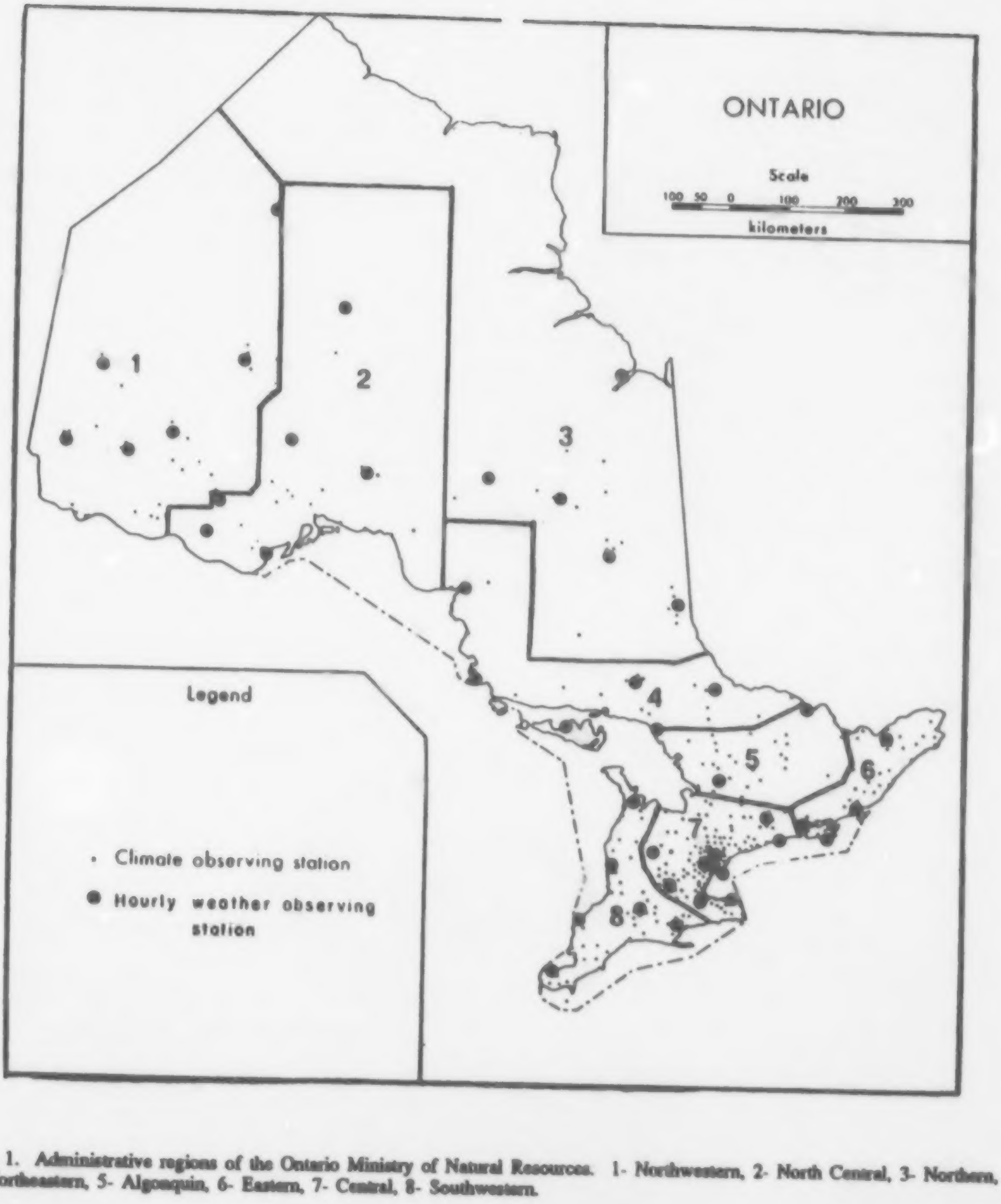

ONTARIO
Scale
100 50 0 100 200 300
kilometers
Legend
• Climate observing station
● Hourly weather observing station
1
2
3
4
5
6
7
8

FIG. 1. Administrative regions of the Ontario Ministry of Natural Resources. 1- Northwestern, 2- North Central, 3- Northern, 4- Northeastern, 5- Algonquin, 6- Eastern, 7- Central, 8- Southwestern.

modified by a factor of 0.85 when the precipitation change was more than 115 percent (new regional temperature is multiplied by 0.85). This change is necessary to better reflect the potential changes in solar noon time temperature when cloud is suggested to be more prevalent (more precipitation) and less prevalent (less precipitation) respectively.

Climate data (and DSRI) values were not available (or very limited) for the months of April and October in all regions. Since it was felt that the suggested climate changes may result in a earlier start and later finish to the fire season, it was necessary to estimate the regional temperature and precipitation values for these months in each region. The monthly mean temperature and total precipitation values based on the 1951-1980 period are available for the two scenario grid systems. In terms of precipitation this information, along with the previously determined regional-grid weighting factors could be used. However, the mean monthly temperatures would not represent the mean solar noon temperatures. To provide an estimate, the scenario grid values of the mean solar noon monthly temperatures in May were used for the mean monthly temperatures in April and the grid values of the mean monthly temperatures in September were used for the mean monthly solar noon temperatures in October. Regional values could then be estimated using the regional-grid weighting factors.

Similar procedures were used to provide estimates of the March and November temperatures and precipitation amounts. However, the resulting temperature and/or precipitation values were beyond the limit of the existing data base and therefore are not included in any further analysis (see Discussion and Conclusions below).

Personal observation: These months may be an important factor particularly in OMNR Regions 5 and 6 where there may possibly be an extension of the fire season into the early weeks of November. However, this further extension of the fire season cannot be shown at this time as this temporal resolution is beyond the limits of this analysis.

The estimates of the impact of climate change as suggested by the two scenarios are calculated on a regional and monthly basis using the previously mentioned polynomial technique.

The climate change regional monthly severity rating index (CCRMSRI) values are calculated by using the appropriate climate change monthly temperature and precipitation values and the equation provided by the polynomial techniques. This procedure is repeated for each of the six regions and for each month from March to October (Table 1).

The ability of the surface to estimate the CCRMSRI values is evaluated by calculating a MODSRI (model severity index) based on the original monthly, regional temperature and precipitation input and the equation defining the appropriate surface. These calculated MODSRI are then compared to the original RMSRI values.

Table 1. Regional Monthly $2XCO_2$

Scenario A-2			Scenario B	Normal Regional Monthly Severity Rating Index
CCRMSRI	OMNR Region	Month	CCRMSRI	RMSRI
0.00	1	4	0.65	-
0.67		5	1.64	1.34
0.56		6	1.00	1.02
1.42		7	.90	1.43
1.63		8	1.31	0.90
0.83		9	1.07	0.64
1.82		10	1.29	-
0.64	2	4	0.47	-
0.56		5	0.94	0.98
0.72		6	0.50	0.99
0.95		7	2.02	1.01
1.28		8	0.51	0.64
0.54		9	0.81	0.39
0.72		10	0.32	-
1.08	3	4	1.02	-
1.35		5	0.95	1.04
1.13		6	1.04	1.26
2.20		7	1.58	1.15
1.19		8	1.42	0.80
1.42		9	0.64	0.27
0.96		10	0.31	-
0.61	4	4	1.01	-
0.85		5	0.86	0.91
0.87		6	0.93	1.06
1.85		7	1.54	1.44
2.26		8	1.32	0.80
0.97		9	0.91	0.36
0.65		10	0.67	-
0.48	5	4	1.16	-
0.75		5	1.11	1.01
1.15		6	1.23	1.09
3.30		7	2.18	1.68
2.76		8	1.86	0.76
1.13		9	1.55	0.84
0.88		10	0.74	-
0.17	6	4	0.78	-
1.24		5	2.04	0.83
1.33		6	1.19	1.35
4.16		7	1.93	1.66
3.23		8	1.70	1.14
1.42		9	1.80	0.82
0.79		10	1.69	-

Discussions and Conclusions

The results presented in Table 1 support the suggestion that climate change as proposed by CO_2 enhancement scenarios will significantly affect the forest fire severity in Ontario. The general trend as indicated by both scenarios' estimates of the CCRMSRI to the RMSRI indicate that the forest fire seasons in all regions will start during the month of April (in all but OMNR Region 1 in Scenario A-2) and will continue into the month of October. The temporal distributions of fire severity within a given fire season as estimated by the two scenarios are somewhat different and to some degree vary with the regions.

CLIMATE CHANGE SCENARIO A-2

The CCRMSRI estimates indicate that in all regions there is a shift from a season that has its most severe months during May, June and July to a season in which the months of July, August and September are most severe. This change is primarily the result of an increase in the amount of precipitation during the early months. In the northern regions (OMNR Regions 1-3) and Regions 4 and 5 the CCRMSRI values during the early months of the season are near or below the normal values despite the fact that the average temperatures have increased. The increased precipitation suggested by the Scenario A-2 during these months more than compensates for the increased temperature and therefore maintains or reduces the CCRMSRI below normal values.

In the Eastern region (OMNR Region 6) the CCRMSRI values are near to somewhat above normal during the early months of the fire season. These values are a result of the near normal precipitation values and higher temperatures suggested by Scenario A-2 during this period for eastern Ontario.

The higher CCRMSRI values in all regions during the latter months of the fire season are a direct result of the increased temperatures and decreased precipitation amounts proposed by the Scenario A-2 for these months in Ontario. The estimated CCRMSRI values are particularly high in the southern regions (OMNR Regions 4-6) during the July to September period when temperatures are suggested to be somewhat higher (3 to 4°C) than normal and the precipitation amounts are much less (10 to 30 mm) than normal.

CLIMATE CHANGE SCENARIO B

The temporal distribution of fire severity as indicated by the Scenario B CCRMSRI values also suggests a shift in the timing of the most severe periods of the fire season. However, in this case the shift is not similar throughout geographically similar regions. The changes in the severity of the fire season are somewhat less than those indicated by the Scenario A-2. This moderation of the suggested impact is a direct result of the enhanced precipitation amount expected generally throughout the season in all regions. The only exceptions to this enhanced precipitation pattern occurs during the months of September and October in OMNR Regions 5 and 6 when scenario precipitation amounts are below the normal levels. However, despite the generally enhanced precipitation, the CCRMSRI values still increase during most of the season from the RMSRI values as direct result of the increased temperatures expected.

In OMNR Region 1 the estimated CCRMSRI values indicate a shift to a bimodal fire season with two high severity periods. The first period, during the months of May and June has severity rating values near to above those of the normal climate. These CCRMSRI values are a result of the higher than normal temperature under this scenario which augment or maintain the near normal severity ratings despite the enhanced precipitation amounts. The second period of higher than normal values in OMNR Region 1 occurs during the months of August, September and October and again the increase is directly related to the higher than normal temperatures suggested by this scenario.

In OMNR Regions 2-4 the CCRMSRI values suggest a shift in the time of higher severity of the fire season from the earlier months of May, June and July to the months of July, August and September. The month of April in OMNR Regions 3 and 4 is also estimated to have a high severity rating as a result of the higher than normal temperatures (approximately 4°C) and the only slightly above normal precipitation amounts (approximately 3 to 5 mm).

The fire severity rating is higher than normal throughout the fire season in both OMNR Regions 5 and 6. In this case, as in the other regions for this scenario, the higher severity is directly related to the higher than normal temperatures. However, during the months of September and October the higher than normal fire severity is associated with not only increased temperatures but with decreased precipitation amounts.

In OMNR Region 5 the fire season starts with a high severity, peaks in July, falls off slightly during August and September but still remains high, and then begins to fall off in October. The extreme value during July is associated with the extreme temperature estimated by this scenario for OMNR Region 5 in July. In OMNR Region 6 the fire severity as suggested by the CCRMSRI values reaches a maximum during the month of May as a result of the almost 4°C increase in temperature and the near normal (increase of only 2.5 mm) precipitation. The CCRMSRI value is reduced somewhat during the month of June from the higher value in May, but returns to higher values in July, August, September and October. As was the case for OMNR Region 5, the higher than normal values during September and October are the result of the combination of higher than normal temperatures and lower than normal precipitation amounts.

The limitations of this analysis are evident when the MODSRI and RMSRI values are compared. These values indicate that the model is more accurate when the severity ratings are not extreme. In all OMNR regions and for both models, the estimates are more accurate at the middle values. The polynomial surfaces tend to underestimate the low values and overestimate the high values. In both cases this is where the data is sparse and the technique is least capable of providing an accurate estimate.

This technique is also less capable of providing accurate estimates when the variables are at or near the limits of the data which went into defining the surface. The estimates in this case would tend to extreme values either high or low. This behavior of the model could account for the extreme CCRMSRI values, particularly those in Scenario A-2 such as OMNR Region 1 in October and OMNR Region 5 and 6 in July and August.

Despite these limits to the technique, the concept of increase length, increased severity and modifications of the temporal distributions of the temporal distributions of the fire severity during the fire season are plausible considering the supplied scenarios. This suggested increase in fire severity will have a significant impact on forestry and the social and economic well-being of Ontario. To better understand this impact it is suggested that a socio-economic study of the impact of this increase in fire severity be undertaken.

References

DIXON, R. 1969. Orthogonal polynomials as a basis for objective analysis. Met. Office Scientific Paper No. 30. London, 20pp.

HENGEVELD, H.C. and R.B. STREET, 1985. Development of CO_2 climate change scenarios for Canadian regions. Canadian Climate Centre, Environment Canada, Toronto. Unpublished.

POLLARD, D.F.W. 1985. A forestry prospective on the carbon dioxide issue. The Forestry Chronicle, Vol. 61(4) 312-318.

VAN WAGNER, C.E. 1970. Conversion of Williams severity rating for use with the Fire Weather Index. Can. Forestry Service, Petawawa Forest Exp. Station Information Report PS-X021. 5pp.

WILLIAMS, D.E. 1959. Fire Season Severity Rating. Department of Northern Affairs and National Resources. Forestry Branch. Forest Research Division Technical Note No. 73. 13pp.

Smoke Management and Air Quality

W.T. SOMMERS
Forest Fire & Atmospheric Science Research
Forest Service, USDA
Washington, D.C.

Abstract

Given that our atmosphere has been electronically active from its most primordial days, we know that fire has been a component of forested terrestrial ecosystems for as long as those ecosystems have existed. Forest fires have always produced smoke. When man entered the picture, among his challenges to nature was his use of fire to help him modify environments to better suit his purposes. Man, like all species, is fairly shortsighted in his endeavours. Whereas other species shortsightedness has been balanced by environmental stress, evolution, or extinction, man has by and large modified his environment at increasingly larger scales of influence. As we near the end of the ninth decade of the twentieth century, fire and man are major, integral factors of our global environment, especially so where the health, productivity, and diversity of forest ecosystems are involved. And while it is generally recognized that fire is a necessary component in the long-term maintenance of those ecosystems, the effect of forest fire smoke on human health, local and regional air quality, and global climate are legitimate concerns we need to address.

In keeping with these concerns and the theme of this Conference, I will address smoke management and air quality in relation to our changing natural and socio-economic environments. Have our forest ecosystems become more fire prone? Will probable global climate change lead us into a period of weather variability likely to increase fire danger? Will people continue to move into proximity with wildlands in ever greater numbers, adding to the fire problem and increasing contact with fire smoke? Can fire smoke be better analyzed as to origin, make-up, and impact? These questions and some suggested answers will be the focus of the address.

Résumé

Étant donné que l'atmosphère a été le siège d'une activité électrique dès ses premiers jours, nous savons que le feu est une composante des écosystèmes terrestres boisés depuis l'avènement même de ces écosystèmes. Les incendies de forêt ont toujours produit de la fumée. Lorsque l'homme est apparu, il a utilisé le feu pour modifier son environnement afin de mieux répondre à ses exigences, lançant ainsi l'un de ses nombreux défis à la nature. L'homme, comme toutes les espèces, n'a pas une vision très étendue des conséquences de ses actions. Le manque de perspicacité d'autres espèces a été équilibré parle stress environnemental, l'évolution ou l'extinction, tandis que l'homme a, généralement parlant, modifié sont environnement et exercé son influence à une échelle sans cesse grandissante. A mesure que nous nous rapprochons de la fin de la neuvième décennie du vingtième siècle,le feu et l'homme sont des facteurs intégrants de taille de l'environnement de la planète, surtout lorsque la santé, la productivité et la diversité des écosystèmes forestiers sont en cause. Bien que tous reconnaissent généralement que le feu est une composante nécessaire de la survie à long terme de ces écosystèmes, les effets de la fumée des incendies de forêt sur la santé de l'homme, sur la qualité de l'air à l'échelle locale et régionale et sur le climat de la planète sont des préoccupations légitimes sur lesquelles nous devons nous pencher.En accord avec ces préoccupations et avec le thème du présent congrès, j'aborderai la gestion de la fumée et la qualité de l'air par rapport ànos environnements naturels et socio-économiques en pleine évolution. Nos écosystèmes forestiers sont-ils devenus plus sujets aux incendies? Les modifications probables du climat à l'échelle de la planète nous plongeront-elles dans une période de variabilité climatique pouvant vraisemblablement faire augmenter les dangers d'incendie? Un pourcentage croissant de la population continuera-t-il de se rapprocher des régions sauvages, aggravant ainsi le problème des incendies et augmentant son exposition à la fumée? Pourrons-nous mieux analyser l'origine, la composition et l'impact de la fumée? Mon exposé portera principalement sur ces questions et offrira certaines tentatives de réponses.

Air Toxics and Fireline Exposure

D.E. WARD
Intermountain Fire Sciences Laboratory,
Intermountain Research Station,
Forest Service, U.S. Department of Agriculture,
Missoula, Montana

Abstract

The 1987 and 1988 forest fire seasons generated concerns about the potential short-term and long-term health effects of firefighters exposed to smoke during fire suppression of wildfires and fire management activities associated with prescribed fires. This concern has prompted a new national initiative to characterize the exposure of fire personnel to emissions from open fires. The Fire Chemistry Project is studying the fuel characteristics, both chemical and physical, affecting combustion leading to the production of air toxics and trace materials. The research approach includes burning modeled fuel arrays in a well instrumented, environmentally controlled combustion laboratory. These experiments will complement knowledge now available that was developed mostly from field experiments.

The combustion efficiency of open fires generally ranges from 60 to 95%. The predominant gases from the combustion of vegetative fuels are carbon monoxide, carbon dioxide, and water vapor. A small fraction of the carbon contained in the fuel is released into the atmosphere in the form of particles. The particles are of major concern, however, because of the high concentration of organic material with the particles, and also because a high percentage of the mass of this particulate matter consists of particles less than 2.5 micrometers in diameter. The small diameter particles can be carried deep into the lungs and contain about 50 to 95% organic carbon with the balance inorganic materials and graphitic carbon. The Polynuclear Organic Material (POM) fraction of the organic carbon content of the particles contains a class of compounds, polynuclear aromatic hydrocarbons (PAH), some of which are known carcinogens. The levels of these materials that fireline personnel are exposed to are not well known. One of the PAH compounds, benzo[a]pyrene (BaP), has been studied in detail, and the concentration is known to increase for both the smoldering combustion phase of fires and in fires burning in live vegetation. Other materials of concern include the high concentration of aldehydes, organic acids, carbon monoxide, and release of deposited materials (e.g., pesticides).

Résumé

Les saisons d'incendies de forêt 1987 et 1988 ont préocupées certains des effets éventuels à court et à long terme sur la santé de l'exposition à la fumée des pompiers luttant contre des incendies de forêt et du personnel de gestion des incendies pratiquant des brûlages dirigés. Ces préoccupations ont mené à la mise sur pied une initiative nationcile pour déterminer les caractéristiques de l'exposition du personnel de lutte aux émissions provenant de feux non contrôlés de projet de chimie forestière étudie les caractéristiques du combustible chimique ainsi que physique affectant la comsustion. Celle-ci entraîne la production de substances toxiques aériennes et de matiénes à l'état de trace. L'approche consiste à brûler des modèles de combustibles diversement agencés dans un laboratoire de combustion bien équipé et à environnement contrôlé. La plupart des connaissances dont nous disposons actuellement proviennent d'expériences effectuées sur le terrain.

L'efficacité de combustion des feux non contrôlés est rarement varie généralement de 60 à 95%. La majeure partie des gaz produits par la combustion de combustibles végétales est du monoxyde de carbone, du dioxyde de carbone et de la vapeur d'eau. Une petite fraction du carbone contenu dans le combustible est libérée dans l'atmosphère sous forme de particules. Ces particules sont toutefois extrêmement préoccupantes en raison de la haute concentration de matières organiques avec les particules et parce qu'un fort pourcentage de la masse de particules se compose de particules de moins de 2.5 micromètres de diamètre. Ces particules infimes peuvent pénétrer très profondément dans les poumons et renferment de 50 à 95% de carbone organique, le reste étant des matières inorganiques et du carbone graphitique. La fraction de matière organique polynucléaire (MDP) de la teneur en carbone organique des particules contient une classe de composés, les hydrocarbures aromatiques polynucléaires (HAP) dont certains sont des agents carcinogènes connus. Nous ne savons pas vraiment dans quelle mesure le personnel de lutte est exposé à ces matières. L'un des composés des hydrocarbures aromatiques polynucléaires, le benzo[a]pyrène (BaP), a été étudié en détail et nous savons que sa concentration augmente pendant la phase de combustion couvante des incendies et dans les feux ravageant la végétation vivante. Parmi les autres matières préoccupantes, mentionnons les fortes concentrations d'aldéhydes, les acides organiques, le monoxyde de carbone et les substances dégagées par les matières déposées (comme les pesticides).

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

Introduction

In the United States during the 1960's, research was initiated to ameliorate the impact of smoke from prescribed fires on local and regional air quality. Since that time, smoke management plans have been successfully implemented in many States and regions. Improvements in methods and techniques for smoke management continue to be developed. Along with the need for more information concerning smoke management, there is a need to investigate the exposures and resulting adverse health effects of smoke on wildland firefighters and personnel involved in prescribed burning operations. This paper summarizes what is known about the content of smoke that may be damaging to human health, what has been learned from research on emissions from prescribed fires that may be relevant to the exposure assessment problem, and several studies evaluating firefighter exposure to carbon monoxide and particulate matter.

Agencies responsible for fire protection have overall responsibility to provide for the safety, health, and well-being of all their employees. There are key statutory and regulatory requirements related to wildland firefighter environmental health and safety. Some have suggested that Federal agencies are exempt from these requirements based on the emergency nature of firefighting. However, the agencies responsible for fire control generally accept responsibility for the health and safety of their personnel. To gain a better understanding of the magnitude of the health problems of firefighters, a comprehensive study plan was prepared for the National Wildfire Coordinating Group (NWCG). The plan recommends a series of studies on smoke from a toxicological standpoint, on levels of exposure to these substances, on health effects observed on the fires, and on types of risk management options needed to minimize the health risks (Ward et al. 1989).

The need for such a study is based on the large numbers of firefighters and fires being suppressed on an annual basis and the health problems observed during the 1987 and 1988 fire seasons. In the United States, about 80,000 firefighters are involved with fire suppression activities on 70,000 wildland fires that burn an average of over 0.8 million ha each year. In 1988, over 2 million ha of land were burned with a total combined suppression cost in excess of $600 million. Over the 4 months of the Yellowstone fires, approximately 40% of the 30,000 medical visits made by wildland firefighters were for respiratory problems. More than 600 firefighters required subsequent medical care. In the Happy Camp Fire Camp for the Klamath Fire Complex in California in 1987, ambient concentrations of carbon monoxide were measured as high as 54 parts per million on a volume basis (ppmv). There is a need to study the exposures, health effects, and management options for personnel involved in fire control and prescribed burning activities.

Burning of carbonaceous fuel produces a complex mixture of combustion products. From classical thermophysics, wildland fires accelerate the oxidation of accumulated biomass over that resulting from natural decomposition. The biomass is a result of basic processes of regeneration, growth, and decline of forest and range systems. The management of the accumulation of biomass through the use of prescribed fire is one way to reduce the size, cost, and severity of wildfires. Typically, biomass contains approximately 50% carbon, 6% hydrogen, and 44% oxygen. Chemical-oxidation reactions involved in burning the biomass produce flames and yield a rapid release of heat. If the chemical reactions were complete, the carbon, hydrogen, and oxygen in the forest fuel would be oxidized to carbon dioxide and water. However, the chemical reactions are never 100% complete, and large quantities of smoke are usually released into the atmosphere. The exposure of personnel to this smoke is of major concern.

Demographic analyses of changes within our society show more people living in the critical zone between urban and wildland environments and an increase in the number of wildland recreationalists. The need for fire protection and fire management has increased dramatically in recent years. The result is a greater demand on wildland and rural firefighters to provide fire protection.

Review of Smoke Components

The mixture of particles, liquids, and gases found in smoke from forest fires is extremely complex and complicates the job of fireline exposure assessment. Uncertainty associated with the potential adverse health effects is much greater because of the complex mixture of materials in smoke. The particles are known to consist of hundreds of important organic compounds that are condensed into tarry droplets over substrate materials of ash or graphitic carbon or both. The particle size distribution is such that a large percentage of material is respirable. Gases in the air adjacent to fires in association with the particles include carbon monoxide, carbon dioxide, methane, oxides of nitrogen, and many organic compounds--some of which are irritants or carcinogens or both. Other materials are classified as semivolatile because they usually occur as condensed liquids with the particles and are in high concentration in the gas phase. The overall toxicity of smoke from vegetative fires has not been evaluated.

The large variance in the concentration of smoke must be evaluated to assess the level of exposure of fireline personnel. Coupled with the mixture and concentration differences of combustion products is the dust, heat, and remoteness of many of the wildland fires and fire camps. The fire, fuel, and weather vary continuously, which changes the fire dynamics and the dilution occurring in the vicinity of where the firefighters work. The smoke may be extremely dense for a few minutes to several hours or days with the air being relatively clean at other times.

Information that is known about the kinds of compounds contained in smoke from wildfires has been inferred from the study of smoke from prescribed (planned) management fires and from controlled laboratory combustion experiments (see section on "Prescribed Fire Research"). A few measurements of concentration have been made in conjunction with attempts to monitor the exposure of firefighters to smoke (see section on "Experience in Fireline Exposure Assessment").

Combustion Products of Concern

Before discussing specific measurements, it is important to gain a general understanding of the chemical components found in smoke and their relative toxicities. In this section, several materials are discussed that are known to be present in smoke from the combustion of biomass fuels. These classes of materials are:

1. particulate matter
2. polynuclear aromatic hydrocarbons
3. carbon monoxide
4. aldehydes
5. organic acids
6. semivolatile and volatile organic compounds
7. free radicals
8. ozone
9. inorganic fraction of particles

Each of these materials is discussed according to what is known about the relative abundance, the production, and briefly why it is toxicologically important.

Particulate matter is highly visible, affects ambient air quality, and has an unknown effect on human health. Particles are abundantly produced by forest fires with source strengths exceeding 0.6 tonnes per second on some large fires (Wade and Ward 1973). The mass of particles can be separated into two distinct modes: (1) a fine-particle mode generally considered to be produced during the combustion of organic material with a mean-mass diameter of 0.3 micrometers, and (2) a coarse particle mode with a mean-mass diameter larger than 10 micrometers. Research, both from ground-based sampling (Ward and Hardy 1984) and airborne sampling systems, has shown this bimodal distribution with a small fraction of the total mass (less than 10%) between 2 and 10 micrometers (Radke et al. in press). The smaller, fine particles are of special concern because they can penetrate the upper respiratory tract and even the alveolar region of the lung. About 40 to 70% of the fine particles consists of organic carbon material (Ward and Hardy 1986). Many known carcinogenic compounds are contained within the organic carbon fraction. Roughly another 2 to 15% is graphitic carbon and the remainder is inorganic ash material (Ward and Core 1986). Particles are also known to carry adsorbed and condensed toxicants and possibly free radicals.

Polynuclear aromatic hydrocarbons are one of the classes of compounds contained in the organic fraction of the fine particle material. Some of the polynuclear aromatic hydrocarbons (PAH) associated with the particles are carcinogenic. Benzo[a]pyrene, for example, is a physiologically active substance that can contribute to the development of cancer in cells of humans. Examples of PAH compounds are listed in Table 1 for prescribed fires in logging slash, laboratory fires of pine needles, fireplaces, and woodstoves. Specific carcinogenic activity and the measured ratio of production of PAH molecules to particulate matter are given. Table 1 illustrates for a few compounds the relative production rates and the variances associated with the production. For example, Ward and Hardy (1986) studied the variance of production of several PAH compounds as a function of loading of live vegetation for prescribed fire units in western Washington and western Oregon. They found for benzo(a)pyrene that emission factors increased as the density of live vegetation covering the prescribed fire units increased.

PAH compounds (e.g., benzo(a)pyrene, chrysene, benzo(ghi)perylene, shown in Table 1) are synthesized from carbon fragments into large molecular structures in low-oxygen environments. Many different combustion systems are known to produce these materials, and the burning of forest fuels is documented as one of these sources. Little is known about combustion conditions on wildfires that optimally produce polynuclear aromatic hydrocarbon compounds. Some combustion conditions produce the compounds more abundantly than others; e.g., for low-intensity backing fires the ratio of benzo[a]pyrene to particulate matter ranged from 98 to 274 micrograms per gram of particulate matter and the same ratio for heading fires was 2 to 3 (McMahon and Tsoukalas 1978). The average values for various PAH compounds and standard deviations are presented in Table 1 for fuel beds of slash pine (*Pinus elliottii* Engelm.) needle litter at three levels of loading and burned using simulated heading and backing conditions.

For wood stoves, a relationship was established between burn rate and PAH production. Specifically, as the burn rate increased, total organic emissions decreased, but the portion that was PAH compounds increased. DeAngeles et al. (1980) found the PAH emission rate to be highest over a temperature range of 500 to 800°C.

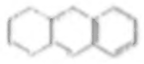
From Table 1, some information exists for open fires, but it is totally inadequate to develop the level of understanding that is needed regarding conditions that would produce harmful levels of these materials in fireline exposure conditions.

Carbon monoxide is a colorless and odorless toxic gas. It is produced through the incomplete combustion of biomass fuels. Carbon monoxide is abundantly produced--second only to carbon dioxide and water vapor. The completeness of the combustion process can be determined by measuring the concentration of carbon monoxide and carbon dioxide. OSHA has

Table 1. Comparison of emissions of polynuclear aromatic hydrocarbons from four sources: (1) prescribed fires in logging slash in western Washington and western Oregon (Ward et al. 1989), (2) pine needle litter fuel of Southeast (McMahon and Tsoukalas 1978), (3) fireplace emissions tests with green southern pine wood (DeAngelis et al. 1980), and (4) woodstove emissions tests with green southern pine wood (DeAngelis et al. 1980). Carcinogenicity is from National Academy of Sciences (1972) and is coded as follows: "-" is not carcinogenic; "±" is uncertain or weakly carcinogenic; "+" is carcinogenic; "++, +++" is strongly carcinogenic.

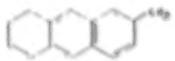
Compound	Logging slash		Pine needles		Fire places	Wood stoves	Carcino-genicity
	Mean	S.D.	Mean	S.D.			
	------(ug of compound per g of particulate matter)-------						
Anthracene/phenanthrene 1/	42	±29	185	±72	575	6345	-/-
Methylanthracenes/ methylphenanthrenes 2/	61	±38			692	3147	
Benz(a)anthracene/chrysene 3/			43	±25	117	2276	+/+
1,2-benzanthracene	17	± 8					+
Chrysene/triphenylene	29	±11					
Dibenzanthracenes/ dibenzphenanthrenes					4	3	
Fluoranthene 4/	47	±23	51	±29	125	1153	-
Benzofluoranthene			11	±11	133	865	
Benzo(ghi)fluoranthene	11	± 5					-
Benzo(a)fluoranthene	7	± 4					
Benzo(b/j/k)fluoranthenes	26	± 9					++/++/-
Pyrene	42	±24	73	±46	133	1153	-
Benzo(a)pyrene 5/	13	±7	3	± 2			+++
Benzo(e)pyrene 6/	13	± 5	6	± 3			-
Benzopyrenes/perylene					117	578	
Perylene	3	± 2	2	± 2			
Indenopyrene	13	±14					
Indeno(1,2,3-c,d)pyrene			N.D.		N.D.	N.D.	+
Anthanthrene/dibenzopyrene	6	± 8			8	1	-
Benzo[ghi]perylene 7/	15	±19	N.D.		117	288	-

1/



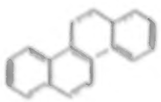
Anthracene

2/



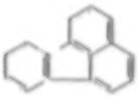
2-methyl-anthracene

3/



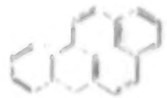
Chrysene

4/



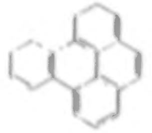
Fluoranthene

5/



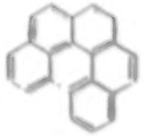
Benzo(a)pyrene

6/



Benzo(e)pyrene

7/



Benzo(ghi)-perylene

published time-weighted-average exposure limit of 50 ppm carbon monoxide for an 8-hour work shift. However, NIOSH generally recognizes 35 ppm carbon monoxide for an 8-hour work shift and 200 ppm as the ceiling exposure with no defined time. Carboxyhemoglobin is created in the blood of humans in response to the exposure to carbon monoxide, which replaces the capacity of the red blood cells to transport oxygen. Generally, a level of 5% carboxyhemoglobin results from 3 to 4 hours of exposure to carbon monoxide of concentrations of 35 ppmv and may result in firefighters showing signs of disorientation or fatigue.

Aldehydes are a class of compounds containing materials that are irritants, some of which have the potential to be carcinogenic. Formaldehyde, a known carcinogen, is probably the most abundantly produced species of this class of compounds and is one compound causing nose, throat, and eye irritation during exposure to smoke. Formaldehyde is transformed rapidly to formic acid in the human body with the formic acid removal rate being extremely slow.

Acrolein is also known to be produced during the incomplete combustion of forest fuels. In smoke from cigarettes, acrolein is about 10 times more plentiful than formaldehyde. Acrolein is known to effect respiratory functions at concentrations as low as 100 ppbv. Studies of pathogenesis in rabbits exposed to smoke from low-temperature combustion of pine wood (Thorning et al. 1982) suggest that low-molecular-weight aldehydes, including acrolein, are the most likely agents of injury (generally injury consisted of lesions in proximal large airways of lungs of rabbits). The ability of scavenger cells in the lung to engulf foreign material or bacteria is decreased through exposure to aldehyde compounds, which may accentuate infections of the respiratory system. Personal communications with Dost (1986) suggest that acrolein has a high likelihood of making a discernible addition to the irritant character of smoke near firelines, and concentrations could be as high as 0.1 to 10 ppmv near fires.

Aldehydes as a class of compounds have been poorly quantified for forest fuels burned in the open environment. Only cursory information is available, and work is now under way to monitor aldehydes during research burns in the field and laboratory.

Organic acids are known to form from the combustion of biomass fuel, but virtually nothing is known about the rates of production or the combustion conditions that are most active in the production of these materials. It is generally recognized that equilibrium conditions set up under high humidity conditions could drive reactions toward the production of organic acids. Generally aldehydes would oxidize to their immediate acidic group under high moisture content conditions. Irritation of mucous membranes would be expected.

Both formic and acetic acids should be present in high concentrations. For example, Kemnitz and Gerstile (1967) reported emission factors for organic acids of 7.5 grams per kilogram of fuel consumed for burning of municipal refuse, landscape refuse, and automobile components. Others have found large emissions of formic and acetic acids in the pyrolysis decomposition products from cellulosic fuels (Richards 1989).

Semivolatile and volatile organic components of smoke contain a wide variety of organic compounds, many with significant vapor pressures at ambient temperatures. Some compounds are partitioned between the gaseous and liquid or solid phases at ambient temperature; e.g., benzene, naphthalene, toluene. Fires are known to produce a variety of these types of compounds, but little characterization work has been done. The phenolic compounds are important substances, with different degrees of volatility, some of which are strong irritants and may be abundantly produced from the partial oxidation of cellulosic fuels. Various phenolic compounds are used as starting materials in the manufacture of resins, herbicides, and pharmaceutical products. Other polynuclear aromatic hydrocarbons of low-molecular weight are contained with the semivolatile class of compounds. Because of the volatility and in some cases reactivity of these compounds, special sampling protocols are required including charcoal adsorption, porous polymer adsorption, and whole-air sampling. These materials are difficult to sample in the environment that firefighters work in, and surrogate methods should be developed to correlate exposures of the more volatile materials with the semivolatile components. Methane and carbon monoxide gases are often produced proportional to other products of incomplete combustion and may serve as indicators.

Free-radicals are abundantly produced through the combustion of forest fuels. The concern lies with how long these materials persist in the atmosphere and their reactivity when in contact with human tissues. Most of the chemical bonding is satisfied through recombination of free-radical groups by condensation within the few seconds of time it takes for the mixture of materials to exit from the flame which should reduce the overall toxicity of these materials. However, some free-radicals persist up to 20 minutes following formation and may be of concern if firefighters are exposed to fresh aerosols. How much of the organic material remains in a reactive, free-radical state is an unknown quantity that needs to be studied to demonstrate either that the time element or the reactivity of this class of materials is not a problem or that additional characterization is required.

Ozone concentrations of concern close to fires would not be expected. Ozone is formed photochemically near the top of smoke plumes under high sunlight conditions. Generally, ozone is formed in situations where smoke is trapped in valleys or under temperature inversion conditions of the atmosphere, or both. Fire crews working at high elevation locations may encounter elevated levels of ozone. Any effort to characterize exposures of firefighters to smoke must account for the potential exposure to ozone in areas where crews are working at elevations close to the top of the atmospheric mixing layer. OSHA standards exist for ozone, and the standard would need to be evaluated in conjunction with the other materials contained in the smoke from burning of biomass materials.

Inorganic materials at trace levels are in smoke particles, dependent on the chemistry of the fuels burned and how intense the fire burns. The natural variability of the mineral content of forest fuels is large enough to affect the chemistry of the content of the emissions. However, the toxicological consequence has not been evaluated. For example, in the Los Angeles Air Basin, particles from fires have been reported to contain high levels of lead in comparison to fires in the Pacific Northwest, probably resulting from years of deposition of materials in that area (Ward and Hardy in press). Special problems have been identified in conjunction with areas of high asbestos where asbestos fibers are carried with the smoke. Areas with high sulfur deposition represent a third example. Organic soils of the Southeast, or fuels in the vicinity of geyser basins in Yellowstone National Park, would be expected to produce emissions of sulfur containing gases when burned.

Prescribed Fire Research

For logging slash fires of the Pacific Northwest and fires in chaparral fuels of southern California, concentrations of emissions were measured directly over the fires (Ward and Hardy 1984, 1986, in press). Samples were collected separately for the flaming and smoldering periods because the flaming and smoldering combustion processes produce emissions with different characteristics. The information presented here clearly illustrates this difference and suggests the kinds of exposures that firefighters would receive if they were exposed to emissions coming directly from the fires. There are relations between different combustion products that may be of value in predicting the production of many complex materials based on the measurement of parameters affecting fire behavior or the measurement of a small number of products of combustion that can be easily measured. A few examples are used in the following paragraphs to illustrate the potential for simplifying the fireline exposure assesssment job.

Data presented in Table 2 demonstrate concentrations exceeding 10 mg/m^3, 50 ppmv, and 0.2 mg/m^3, for particles less than 2.5 micrometers diameter, carbon monoxide, and benzo[a]pyrene, respectively. Fuel, fire, and atmospheric dilution processes all contributed to the variances observed in the measured concentrations listed in Table 2. The concentration of particles in the convection column above fires is high (maximum of 28.3 mg/m^3) but extremely variable and ranges down to a low measured concentration of 0.2 mg/m^3 during the smoldering combustion phase.

From Table 2, the concentration of particles less than 2.5 micrometers in diameter is correlated with the concentration of carbon monoxide ($r = 0.89$). This correlation suggests that carbon monoxide concentration may be predicted based on the concentration of particles less than 2.5 micrometers in diameter. From other research, it has been demonstrated that the concentration of particles can be inferred from visual range (Southern Forest Fire Laboratory 1976). A corollary to this is that if measurements of exposure to carbon monoxide can be made, then the exposure to particles can be inferred. These kinds of analyses need to be expanded to reduce the overall complexity of the field monitoring job and to reduce the cost of measuring personal exposure on the fireline.

For the flaming phase (Table 2), the particulate matter concentrations are nearly perfectly correlated with the concentration of benzo[a]pyrene ($r = 0.999$). The same correlation did not hold for the smoldering combustion phase. Other indicator compounds, such as the concentration of volatile hydrocarbon compounds, may be more closely linked to the concentration of benzo[a]pyrene. Correlations with other classes of compounds have not been tested.

To summarize the work of Ward and Hardy (1986) for prescribed fires in the Western United States, they found: (1) emissions of particulate matter range over a factor of 10 dependent on fire and fuel conditions that affect combustion efficiency; (2) brushy areas produce the most smoke per ton of fuel consumed and have higher rates of production of benzo[a]pyrene than nonbrushy units; (3) fires of higher intensity (long flame lengths) produce proportionately larger particles than are found in low intensity and smoldering combustion fires; (4) carbon monoxide is abundantly produced from open fires and generally, on a mass basis exceeds the production of particles by a factor of 10; and (5) hydrocarbon gases are a small part of the total amount of carbon released from the combustion of forest fuels.

Virtually no measurements exist for aldehydes, organic acids, ozone, semivolatile organics, and free-radical materials at ground level. Some information exists regarding the production of particulate matter, benzo[a]pyrene, carbon monoxide, methane, and carbon dioxide. It is extremely important that emissions characterization be performed for a wider range of fuel types and burning conditions and that the other compounds of concern be evaluated to interpret exposures of fireline personnel to smoke.

Other information from prescribed fires and modeled fuel complexes burned under controlled laboratory conditions are available to assess fireline exposure evaluations. Worst-case situations should be evaluated because the adverse health effects are not known and may be difficult to quantify for the average exposure conditions. There are cases of exposure to smoke that can be identified as causing severe irritation to eye, throat, and lung tissues. Examples include prescribed fires of recently herbicide-treated brush vegetation on the West Coast where the underlying duff fuels are moist but with a heavy loading of fine fuels. The fires often burn with a high rate of energy release and smoldering combustion persists for long periods in the

Table 2. Emission factors (grams of pollutant produced per kilogram of fuel consumed) and concentrations of carbon monoxide, fine particles, and benzo[a]pyrene measured from prescribed fires in Oregon and Washington during 1983 and 1984 (Ward and Hardy 1986). (Flaming phase - 0 to 20 minutes after ignition, smold.1 - 20 to 80 minutes after ignition, smold.2 - 80 to 200 minutes after ignition.)

Test Area	Phase of combustion	Emission factor		Concentration		
		Carbon monoxide (g/kg)	Particulate matter (g/kg)	Carbon monoxide (ppmv)	Particulate matter (mg/m^3)	B[a]P (µg/m^3)
CAT	Flaming	112	13	146	19.4	.158
HEBO	Flaming	94	16	113	21.7	.177
MARIA1	Flaming	101	12	134	18.4	.150
MARIA2	Flaming					
DLAKE1	Flaming	82	10	202	28.3	.231
DLAKE2	Flaming	56	6	191	21.3	.174
BE1	Flaming	66	7	21	2.4	.020
BE2	Flaming	50	4	88	8.5	.069
BE3	Flaming	28	1	72	3.5	.029
WCB1	Flaming	63	4	256	20.6	.168
WCB2	Flaming	63	4	180	13.3	.108
CAT	Smold.1	198	18	75	7.6	.183
EBO	Smold.1	231	14	29	2.0	.145
MARIA1	Smold.1	201	14	224	17.8	.146
MARIA2	Smold.1	359	34	15	1.6	.356
DLAKE1	Smold.1	130	11	34	3.3	.118
DLAKE2	Smold.1	196	11	93	6.1	.118
BE1	Smold.1	233	18	114	10.1	.189
BE2	Smold.1	222	13	120	7.9	.133
BE3	Smold.1	220	15	334	25.7	.155
WCB1	Smold.1	251	11	77	3.8	.111
WCB2	Smold.1	252	11	129	6.4	.115
CAT	Smold.2	197	9	22	1.2	.107
HEBO	Smold.2					
MARIA1	Smold.2	260	12	63	3.3	.138
MARIA2	Smold.2	358	22			
DLAKE1	Smold.2	156	29			
DLAKE2	Smold.2	222	13	29	1.9	.146
BE1	Smold.2	180	8	15	0.8	.094
BE2	Smold.2	54	6	3	0.4	.066
BE3	Smold.2	248	42			
WCB1	Smold.2	393	4	22	0.2	.044
WCB2	Smold.2	460	11	27	0.7	.122

decomposed fuels. Emissions from these kinds of fires are known to contain high ratios of PAH compounds to particulate matter and may produce large quantities of other partially oxidized organic compounds, i.e., organic acids and aldehydes.

In the Southeastern United States, laboratory test fires of modeled pine needle litter fuel beds produce high ratios of benzo[a]pyrene to particulate matter for backing fires in comparison to heading fires. This particular set of conditions needs further evaluation because emissions from backing fires could be an extreme case for the production of the known carcinogenic substance.

Carbon monoxide was found to be produced in the highest ratio to the fuel consumed during the smoldering combustion phase. However, the concentration of carbon monoxide in the smoke was high during the flaming combustion phase when the rate of fuel consumption was highest (see Table 2). Under these conditions, at least two classifications of workers would receive maximum exposures: (1) personnel involved in frontal attack of a spreading fire working close to the fire front, and (2) personnel involved in mop-up operations during the early stage of the diedown period at the termination of flaming combustion and beginning of smoldering. Additional work is needed in both of these cases and others to define the levels of exposure by job classification.

Experience in Fireline Exposure Assessment

Several independent studies have been performed over the past 15 years to evaluate the exposure of fireline personnel to smoke. Many factors complicate these investigations and must be considered in future measurements of exposure:

1. Firefighters often work 12 to 24 hour shifts during initial attack of wildfires. This complicates the use of normal workplace industrial hygiene methods.

2. The composition of the particles is extremely complex and many times has a significant dust component. Therefore, future methods must consider the aerosol characteristics in designing the sampling protocols.

3. The exposure levels are highly variable, which makes the industrial hygiene sampling difficult.

4. Everyone understands the difficult terrain, frequent high-temperature exposures, and dusty conditions associated with firefighting activities. Few understand the complexity of sampling combustion products from open combustion sources burning under a wide range of air-to-fuel ratios, moisture contents, and fuel composition conditions. The level of complexity introduced by these other variables makes the job of fireline exposure assessment extremely difficult.

Considering all of the complicating factors, some useful information has emerged from the studies performed. Six studies are listed here.

EQUIPMENT DEVELOPMENT CENTER--1974-1976.

The Missoula Equipment Development Center (Jackson and Tietz 1979) performed exhaled breath, carboxyhemoglobin analyses on 1,661 nonsmoking firefighters on 22 separate fires (11 wildfires and 11 prescribed fires). Results indicate that 159 of the firefighters had carboxyhemoglobin levels above 5%. The combined effect of other products of incomplete combustion and heat stress coupled with carbon monoxide have not been examined. Initial attack crews were identified as the personnel receiving the highest levels of exposure.

HAPPY CAMP FIRE COMPLEX (1987)

Data from the local Air Quality Management District stations indicated that ambient levels of carbon monoxide at Happy Camp, the incident command center for the Klamath Fire Complex in northern California during 1987, exceeded 50 ppm for one period of about 1 hour (California Department of Health Services 1989). Biological monitoring (exhaled breath) for carbon monoxide indicated that cigarette smoking (first) and time on the fireline (second) were the most important determinants of dose. Of those tested, 18% exceeded the level of exposure that would produce 5% carboxyhemoglobin (California Department of Health Services 1989). Air sampling results indicated the greatest exposure--in excess of 200 ppm carbon monoxide--occurred near operating gasoline engines during pumping activities. Benzene samples were generally at or below the limit of detection. Total dust levels ranged from 1.8 milligrams per cubic meter of air at base camp to 17.5 milligrams per cubic meter of air on the fireline. Coughs and headaches were frequently reported symptoms described by firefighters.

BURNEY AND MT. CAMPBELL, MT. LASSEN AREA OF CALIFORNIA (1988)

This study focused on smoke exposure to firefighters engaged in mop-up operations on the fireline during two timber fires in Northern California. Total dust was collected and analyzed for mass and for 12 polynuclear aromatic hydrocarbons (PAH). Blood samples were collected from firefighters to measure uptake of harmful chemicals by the body. In addition, colorimetric indicator tubes and direct reading instruments were used to estimate exposure to carbon monoxide and oxides of nitrogen. Industrial hygienists remained with the fire crews during sampling to observe how work practices related to exposure.

PAH of known carcinogenicity were recovered from all 22 samples collected. Total PAH levels averaged about 0.9 micrograms per cubic meter. Concentrations of individual PAH compounds were measured and varied over one order of magnitude among samples.

Total dust levels varied widely with maximum levels of 37.5 milligrams per cubic meter, which exceeds the permissible exposure limit for nontoxic dusts. Carbon monoxide levels exceeded 200 parts per million adjacent to gasoline-powered pumping engines. Carbon monoxide levels varied widely during fire suppression activities ranging from 3 in "clean" air on the fireline to 80 parts per million in plumes of smoke from smoldering areas. Carbon monoxide levels were extremely variable locally.

PRESCRIBED FIRE CREWS OF PACIFIC NORTHWEST-(1988-1989)

Four prescribed burns were monitored in 1988 for carbon monoxide and formaldehyde (Reinhardt 1989). Results suggest that prescribed burning has a potential for brief overexposure of firefighters to several air toxics in smoke but that well-managed burns minimize the smoke exposure hazards. Time-weighted averages measured on the prescribed fires were no higher than 26 ppmv for carbon monoxide and no higher than 0.212 ppmv for formaldehyde. Both are within safe limits by NIOSH standards.

Many more tests are planned for 1989 in conjunction with prescribed burning programs in the Pacific Northwest and California. The tests will provide new information concerning exposures of personnel and will be used as a pilot-scale test for sampling methods, correlation analyses, and ranges of exposures as functions of a multitude of variables.

FIRELINE EXPOSURE ASSESSMENT BY NIOSH FOR THE YELLOWSTONE FIRES-(1988)

NIOSH performed personal monitoring for a number of crews on the Yellowstone fires of 1988 at the request of the National Park Service (Reh 1989). The survey consisted of personal breathing zone air sampling for carbon monoxide, carbon dioxide, sulfur dioxide, and oxides of nitrogen. Area sampling was performed for the above compounds and aldehydes, PAH compounds, total particulate matter, and volatile and semivolatile hydrocarbons. The highest carbon monoxide level recorded was 23 ppmv. Personal breathing zone samples for sulfur dioxide were between 0.5 and 5.0 ppmv.

FIRELINE EXPOSURE ASSESSMENT ON MANAGEMENT FIRE IN SOUTHEAST (1988).

The USDA Forest Service and University of Georgia in the southeastern United States performed personal breathing zone and area sampling of prescribed fires where herbicides had been used to defoliate the vegetation prior to burning (McMahon 1989). No herbicide residue was found. Breathing zone samples of particulate matter ranged from 350 to 4000 micrograms per cubic meter of air sampled for periods of 1 to 5 hours.

SUMMARY OF FIRELINE EXPOSURE ASSESSMENT

The existing set of case histories serves to illustrate the wide range of exposures encountered by firefighters. These measured exposures, in general, are quite low. Fireline exposure assessment protocols need to be developed to systematize the characterization of emissions, the duration of exposure, and the specific job of the firefighter. Measurements of exposure for hand crews are not representative of exposures for operators of pumper trucks. Dust associated with many activities far exceeds the level of exposure to smoke particles. Carboxyhemoglobin levels are high in some cases and special attention needs to be given to monitoring for carbon monoxide exposure. Other materials have not been quantified nor do good methods exist for measuring the exposure of fireline personnel to organic acids, PAH compounds, and other reactive materials.

Conclusions

The agencies responsible for the management of fires in wildland vegetation (both the control of wildfires and the execution of managed fires) are aggressively seeking information concerning the potential adverse risk of exposure of fire personnel to smoke. New information is needed regarding what is in smoke, the toxicity of the smoke, and the concentrations and time of exposure to the smoke.

Considerable knowledge exists regarding the content of smoke from prescribed fires in wildland fuels. These measurements suggest that simplified sampling techniques can be developed using easily measured compounds to predict other compounds that are more difficult to sample and to assess using analytical techniques. If the development of surrogate sampling methods is successful, a large data base can be developed concerning the exposure of fire management personnel to smoke.

Large variances exist associated with the production of smoke combustion products and exposure to the materials of concern. Toxicity of the combination of combustion products is dependent on the relative concentrations of the individual compounds as well as the overall concentration and length of exposure. There are individual toxicities associated with many of the compounds found in smoke. The combined toxicity of these substances is not known. A detailed set of studies is being planned by the National Wildfire Coordinating Group to provide answers so that risk management options can be exercised.

References

CALIFORNIA DEPARTMENT OF HEALTH SERVICES. 1989. [Personal Communication] January 11, 1989. San Diego, CA: J.R. Jones, California Department of Health Services, 2151 Berkeley Way, Berkeley, CA.

COOPER, J. 1980. Environmental impact of residential wood combustion emissions and its implications. J Air Pollut. Control Assoc. Vol 30:(8)

DEANGELIS, D., D. RUFFIN, AND R. REZNIK. 1980. Preliminary characterization of emissions from wood-fired residential combustion equipment. Final Report to U. S. Environmental Protection Agency, EPA-600/7-80-040.

DOST, F. 1986. A consideration of acute toxicologic responses to components of vegetation smoke. Unpublished draft supplied to author by Frank Dost January 11, 1989.

JACKSON, G., AND G. TIETZ. 1979. A preliminary analysis of employee exposure to carbon monoxide on wildfires and prescribed burns. USDA For. Ser. Equipment Development Center.

KEMNITZ, D., AND R. GERSTLE. 1967. Atmospheric emissions from open burning. J. Air Pollut. Control Assoc. 17:324-327.

MCMAHON, C. 1989. [Personal Communications] January 11, 1989. C.K. McMahon, Andrews Forestry Sciences Laboratory, Devall St, Auburn University, Auburn, AL.

MCMAHON, C, AND S. TSOUKALAS. 1978. Polynuclear aromatic hydrocarbons in forest fire smoke. In P.W. Jones, and R.I. Freudenthal, eds. Carcinogenesis, Vol. 3:Polynuclear Aromatic Hydrocarbons. Raven Press, New York.

NATIONAL ACADEMY OF SCIENCES, COMMITTEE ON BIOLOGIC EFFECTS OF ATMOSPHERIC POLLUTANTS 1972. Particulate polycyclic organic matter. Washington, DC.

RADKE, L., J. LYONS, P. HOBBS, D. HEGG, D. SANDBERG, AND D. WARD. (In Press) Airborne monitoring and smoke characterization of prescribed fires on forest lands in western Washington and Oregon--final report. USDA For. Ser. Gen. Tech. Rep., Pacific NW Res. Sta.

REH, C. 1989. [Personal Communications] January 11, 1989. San Diego, CA: C.M. Reh, NIOSH, Cincinnati, OH.

REINHARDT, T. 1989. Monitoring firefighter exposure to air toxics at prescribed burns of forest and range biomass. In Proceedings of Pacific Northwest International Section of Air and Waste Management Association Specialty Conference on Combustion and the Environment. March 8-10, 1989. Seattle, WA.

RICHARDS, G. 1989. [Personal Communications] March 16, 1989. G. N. Richards, University of Montana, Wood Chemistry Laboratory, Missoula, MT.

SOUTHERN FOREST FIRE LABORATORY. 1976. Southern forestry smoke management guidebook. USDA For. Ser. Gen. Tech. Rep. SE-10, Southeastern For. Exp. Sta.

THORNING, D., M. HOWARD, L. HUDSON, AND R. SCHUMACHER. 1982. Pulmonary responses to smoke inhalation: morphologic changes in rabbits exposed to pine wood smoke. P. 355-364. Human Pathology Vol 13(4) April.

WADE, D., AND D. WARD. 1973. An analysis of the Air Force bomb range fire. USDA For. Serv. Res. Pap. SE-105, Southeastern For. Exp. Sta.

WARD, D., AND J. CORE. 1986. Source emission profiles for Douglas-fir and hemlock slash burning. In Proceedings, Annual Meeting Pacific Northwest International Section Air Pollution Control Association; November 12-14, 1986. Portland, OR.

WARD, D., AND C. HARDY. 1984. Advances in the characterization and control of emissions from prescribed fires. P. 1-32. In Proceedings of 78th Annual Meeting of the Air Pollution Control Association, San Francisco, CA., Pap. 84-36.3.

WARD, D., AND C. HARDY. 1986. Advances in the characterization and control of emissions from prescribed broadcast fires of coniferous species logging slash on clearcut units. Final Report to U. S. Environmental Protection Agency and the U. S. Dept. Energy. Project EPA DW12930110-01-3 and DOE DE-A179-83BP128-69.

WARD, D., AND C. HARDY. (In Press) Emissions from prescribed burning of chaparral. P. 1-22. In Proceedings of 1989 Annual Meeting of Air and Waste Management Association, Anaheim, CA., Pap. 89-025.005.

WARD, D., N. ROTHMAN, AND P. STRICKLAND. 1989. The effects of forest fire smoke on firefighters--a comprehensive study plan. A special report for Congressional Committee of Appropriations for Title II--Related Agencies. USDA For. Ser. and Nat. Wildfire Coord. Group. USDA For. Serv. Intermt. Res. Sta.

Automatic Smoke Management System (ASMS)

R. GILBERT
MeteoGlobe Canada Inc.
Roxboro, Quebec

Abstract

The presentation described the system ASMS which is now in development at Meteoglobe Canada Inc. The system is designed to be used in smoke management, environmental emergencies and air quality studies. The system, based on a portable micro-computer, will automatically gather data from a surface meteorological station and from a mini-sound tracking system controlled by the computer. A boundary layer model will forecast temperature and wind profiles for the first thousand meters of the atmosphere. A dispersion model will predict behavior of the column fire and its associated plume. Outputs as aerosols and gases emission rates, heat released (or plume height by convective-lift), time-space plume evolution, downwind concentration, will be computed by the micro-computer. These results will be displayed on the screen and on a portable printer and will be stored on disk. A data base which includes information on toxicity of dangerous chemicals and their impacts on health and on the environment will be added. All components are battery operated which give autonomy to the system and make it an important tool in emergency situations.

Résumé

La présentation décrira brièvement le système SAGBD actuellement en développement à Météoglobe Inc. Ce système pourra êtra utilisé dans la gestion de la fumée, les urgences environnementales et les études en qualité de l'air. Le ceveau du système est constitué d'un micro-ordinateur portatif qui s'occupe de l'acquisition des données au sol et de la poursuite d'une mini-radiosonde par des antennes orientées par un moteur, lui-même contrôlé par l'ordinateur. Un modèle génèrera les prévisions des profils de température et de vent dans la couche limite atmosphérique. Un modèle de simulation de transport et de dispersion des polluants décrira l'évolution spatio-temporelle du comportement d'une colonne de feu et de son panache de fumée. Des résultats tels que: les taux d'émission des aérosols et des gaz, leurs concentrations en aval du panache, la chaleur libéré par la colonnée de feu (ou la hauteur de montée du panache), les zones polluées dangereuses,...seront calculés par l'ordinateur. Ces informations paraîtront à l'écran ou sur imprimante et seront mémorisées sur disquette. Une base de données sur les substances toxiques et leur impact sur la santé et l'environnement sera ajoutée. Toutes les composantes fonctionnent à pile ce qui confère un caractère autonome au système et permet d'en faire un outil précieux dans les situations d'urgence environnementale.

Protecting the Health and Productivity of the Boreal Estate

D.C. MACIVER
Canadian Climate Centre
Atmospheric Environment Centre
Environment Canada
Toronto, Ontario

Abstract

The Boreal Region of Canada is a fragile and sensitive ecosystem that has evolved from a mosaic of catastrophic events, especially fire.

The productivity of a tree is represented each year by the height increment added to the stem and the layering of new wood by the cambium. The health and vigor of trees are reflected in the longitudinal variation and thickness of the annual growth layer. Patterns of successive changes in this growth layer integrate much of its history, particularly the influence of climate.

The monitoring of these radial and longitudinal patterns of growth required the development of a computerized Tree Ring Increment Measuring (TRIM) system; unit area mapping of all species; destructively sampled and replicated plots per stand; and detailed within tree sampling designs.

Physio-climate models for Jack Pine (Pinus Banksiana Lamb) in Ontario document the growth and development patterns for "healthy" stands; the diagnosis of departures; and the identification of the possible causative agents.

Improved suppression technologies will continue to protect the forest community and the populations that reside within from recurrent catastrophic events. New preventive forest management directions will focus on intensive and shorter production rotations of genetically "resistant" and healthy species on climatically sustainable sites. The higher investments needed to establish and maintain these sites will shift the priority of protection resources within the forest estate.

Résumé

La région boréale du Canada est un écosystème fragile et vulnérable, aboutissement d'une mosaïque d'événements catastrophiques, en particulier l'incendie. La productivité annuelle d'un arbre est représentée par l'augmentation de sa hauteur, ajoutée à la tige, et par l'ajout d'une couche de nouveau bois par le cambium. La santé et la vigueur des arbres se reflètent dans la variation et l'épaisseur longitudinales de la couche de croissance annuelle. La configuration des changements successifs de cette couche de croissance intègre une bonne partie de l'histoire de l'arbre, en particulier l'influence de climat. La surveillance de la configuration radiale et longitudinale de la croissance a nécessité la conception d'un système informatisé de mesure de l'augmentation des cernes des arbres (TRIM); l'établissement de cartes unitaires de toutes les espèces; des parcelles échantillonnées et reproduites, par voie destructive, par peuplement; et détaillées dans les modèles d'échantillonnage des arbres. Les modèles physioclimatiques du pin gris (Pinus Banksiana Lamb) de l'Ontario étayent la configuration de la croissance et du développement des peuplements "sains"; le diagnostic des écarts; et la détermination des causes éventuelles. Les techniques améliorées de suppression continueront de protéger les milieux forestiers et leur population contre les catastrophes périodiques. De nouvelles orientations de gestion préventive des forêts se concentreront sur des rotations intensives et plus courtes, dans des emplacements au climat adapté, d'espèces saines et "résistantes" au point de vue génétique. Les investissements plus élevés qu'il faudra pour établir et entretenir ces emplacements feront se déplacer la priorité des ressources de protection dans les terres forestières.

Introduction

The Boreal Estate in Canada is a fragile and sensitive ecosystem that has evolved from a series of catastrophic events, especially fire into a mosaic of vegetative patterns with differential health and productivity profiles. Silvicultural preparations following forest logging activities create renewal opportunities, in much the same manner as prescribed burning for the successful regeneration of healthy forest stands. However, in many cases, this is a difficult and complex achievement under changing climate conditions.

The selection of individual survivors within a forest stand and the identification of candidates for mortality happen at an early age as the trees are competing for light, temperature, moisture and space. Other aperiodic stress events will accelerate tree stagnation and, if independently severe or coincident will lead to incremental mortality. This integrated history is recorded in the annual growth layers from the age of seed - both for individual trees and the forest stand.

The degree of growth response is principally governed by the current stand structure, growth history,

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

soil, physiographic and climate, limiting factors. By focusing initially on the macrocausative factors of stand structure, soils and climate and by isolating their individual and interactive influences, other coincident stress events can be identified. This is definitely a hierachial process by which we first attempt to understand what we can, then address departures or residual patterns separately.

Health and Productivity Monitoring

The changing status of the health and productivity of the forest estate dictates a need for a physiological interpretation of forest growth and development based on a dynamic rather than a static understanding.

Within this context, climate plays a major role. If accelerated growth responses are expected compared with the natural stand, the scheduling of forest management activities must be "in sync" with the dynamics of the climate environment. Otherwise, trees will be subjected to increasing competition stress coupled with recurrent climate stress episodes. Under these conditions, significant declines in health and vigour will be accompanied by slowdowns in productivity and extended rotation periods.

To unravel the complexity of these biological responses required the development of a computerized Tree Ring Increment Measuring (TRIM) system (Fayle and MacIver 1986) (see figure 1).

In order to understand the physiological-climate linkages, trees were sectioned at sufficiently close intervals to document the detailed radial and longitudinal patterns of growth. Specifically, trees within four randomly replicated 10x10 metre plots per stand were sectioned at 15 cm. intervals between the base and breast height and again within the final 2 metres from the apex. The remaining stem portion was sectioned at 45 cm. intervals for Jack Pine (Pinus Banksiana Lamb) compared to 30 cm. intervals for Black Spruce (Picea mariana (Mill.) B.S.P.). Each tree disk section was measured with the TRIM system along a minimum of 2 cardinal radii (north-south).

The surrounding plot buffer resulted in a total plot size equal to 20x20 metres. Within this total plot area all morphological characteristics were recorded and the location of each tree was mapped.

Individual tree indices (ie. height, volume, specific volume increment, etc...) were also aggragated into plot and forest stand profiles within the stratified context of competition and soil texture classes. In all cases, the growth layer was the basic unit of measure.

Species Sensitivity to Climate

Trees grow at their optimum rates under balanced temperature and moisture conditions specific for that species. An imbalance in one or the other condition or

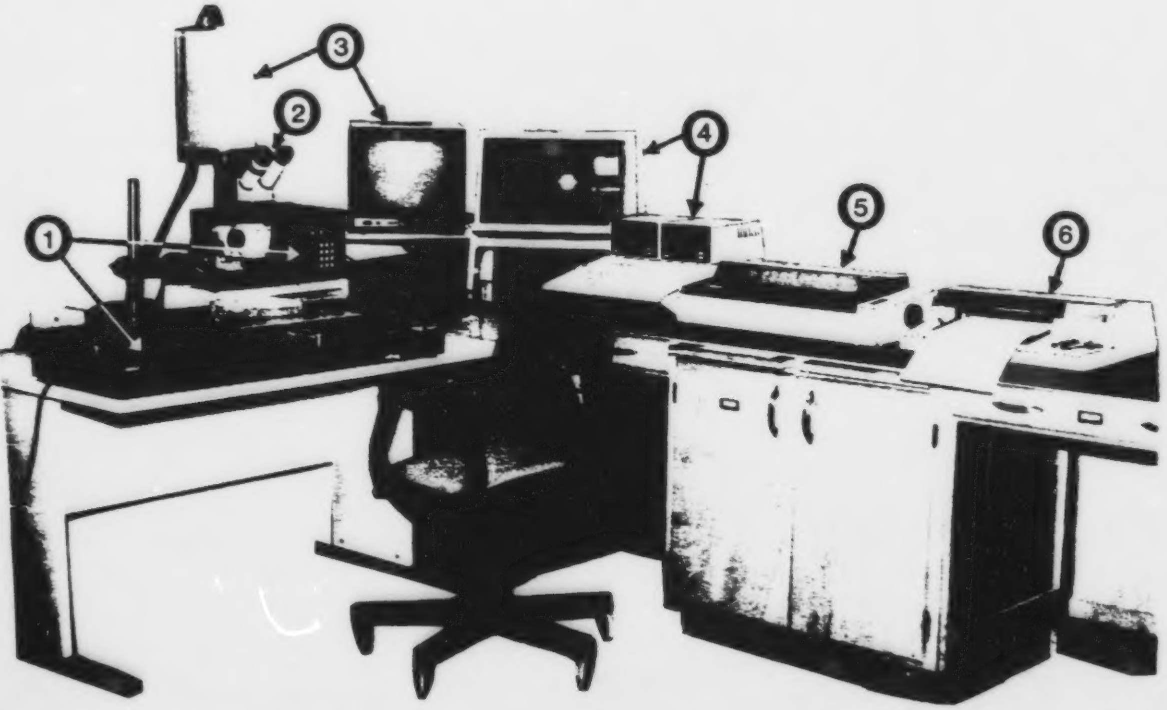


FIG 1. TRIM system showing (1) measuring table and Sony controller; (2) stereomicroscope; (3) TV camera and monitor; (4) Apple IIe microcomputer system; (5) 132 column Epson printer; (6) Hewlett-Packard 6-pen plotter.

both results in a deterioration of the health of the tree accompanied by slowdowns in volume productivity. Similar or accelerated rates of volume slowdown can also be experienced, either independently or coincident with the climate stress events, from competition increases or improper allocation of species to soil texture class. Within this context, a stratified approach was applied to the TRIM data bases to isolate and evaluate the individual contributions of each macrocausative influence - competition, soils and climate.

A quadrat based competition algorithm was first developed to stratify the spatial tree patterns within the replicated plots per stand into uniform, random or clustered classes. This algorithm for all species compared to the commercial crop species can be conceptualized as a species space in which the three basic classes are increasing axes in a multidimensional space. As the percentage contribution of each class approaches the centroid, volume productivity understandibly declines.

In addition to this static evaluation, the dynamic evaluation of the effective crown base (Fayle and MacIver 1986) was historically recreated and compared to the base of live crown.

Competition and short-duration episodic events will accelerate the separation between these two base levels. The degree of separation provides both an immediate and historical bioassay of the health status of the tree and forest stand plus future growth recovery potential. For example, healthy non-competing trees demonstrate little separation between these base levels over time, with minimal growth losses during stress episodes followed by superior growth recovery.

Thermal stress periods were defined by the previous October and current April mean monthly temperatures compared to the Specific Volume Increment for Jack Pine. Moisture stress was identified by the total annual water deficit by soil texture class (based on Thornthwaite methods).

The integrated effects of thermal and moisture stress by mean stand volume are illustrated in the nomogram in figure 2.

The climate thresholds (T) and associated ranges for different levels of productivity are identified for the base-line reference of clustered young Jack Pine stands on sand soils. The central portion of the nomogram demonstrates the balance between temperature and moisture needed for high volume productivity. Any departures from this central zone either wetter/drier or colder/warmer result in significant volume slowdowns, declining health, longer rotations and greater tree stagnation and mortality, especially under coincident stress episodes (ie. insects, disease, extreme climate events).

Of particular note is the narrow range of optimum temperatures for Jack Pine and therefore the high degree of sensitivity to both annual and long-term changes in climate. In comparison, Black Spruce has a lower sensitivity with higher threshold temperatures and a wider temperature range.

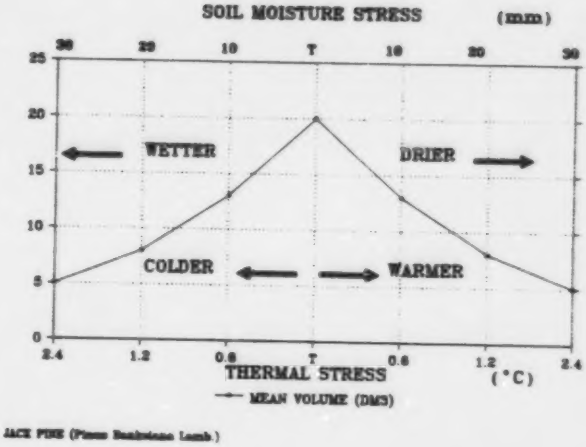


FIG 2. This nomogram illustrates the relationship between thermal and moisture stress related to mean volume production.

The spatial distribution of the provisional productivity regions for Jack Pine in the Ontario Boreal Estate are illustrated in figure 3. Significant productivity differences can be expected from one region to the next (50% less mean volume in region 2 compared to region 1 by 20 years). For example, over short geographical distances, regions can change from levels of high (1) to low (3) productivity with a compression of the intermediate productivity region (2). This occurs principally when crossing the southern boundary of the Boreal Estate for both Jack Pine and Black Spruce. The patterning of the productivity regions highlights the dominance of the continental air masses in the northwestern areas of Ontario, whereas the northern and northeast areas are influenced by southerly frontal intrusions with significant modification by the Great Lakes, especially Lake Superior.

Protection Strategies

The forest species in the Boreal Estate of Canada are extremely sensitive to annual and long-term changes in the balance between temperature and moisture. Species with higher climate sensitivities are at higher risk both directly and indirectly from climate-induced changes.

Improved prevention and suppression technologies will be needed to protect current forest environments and the populations that reside within.

The degree of health deterioration, volume slowdown, tree stagnation and mortality are a function of the competition status of the stand at the onset of the thermal/moisture stress period. Coincident bursts of mortality induced by other agents will further accel-

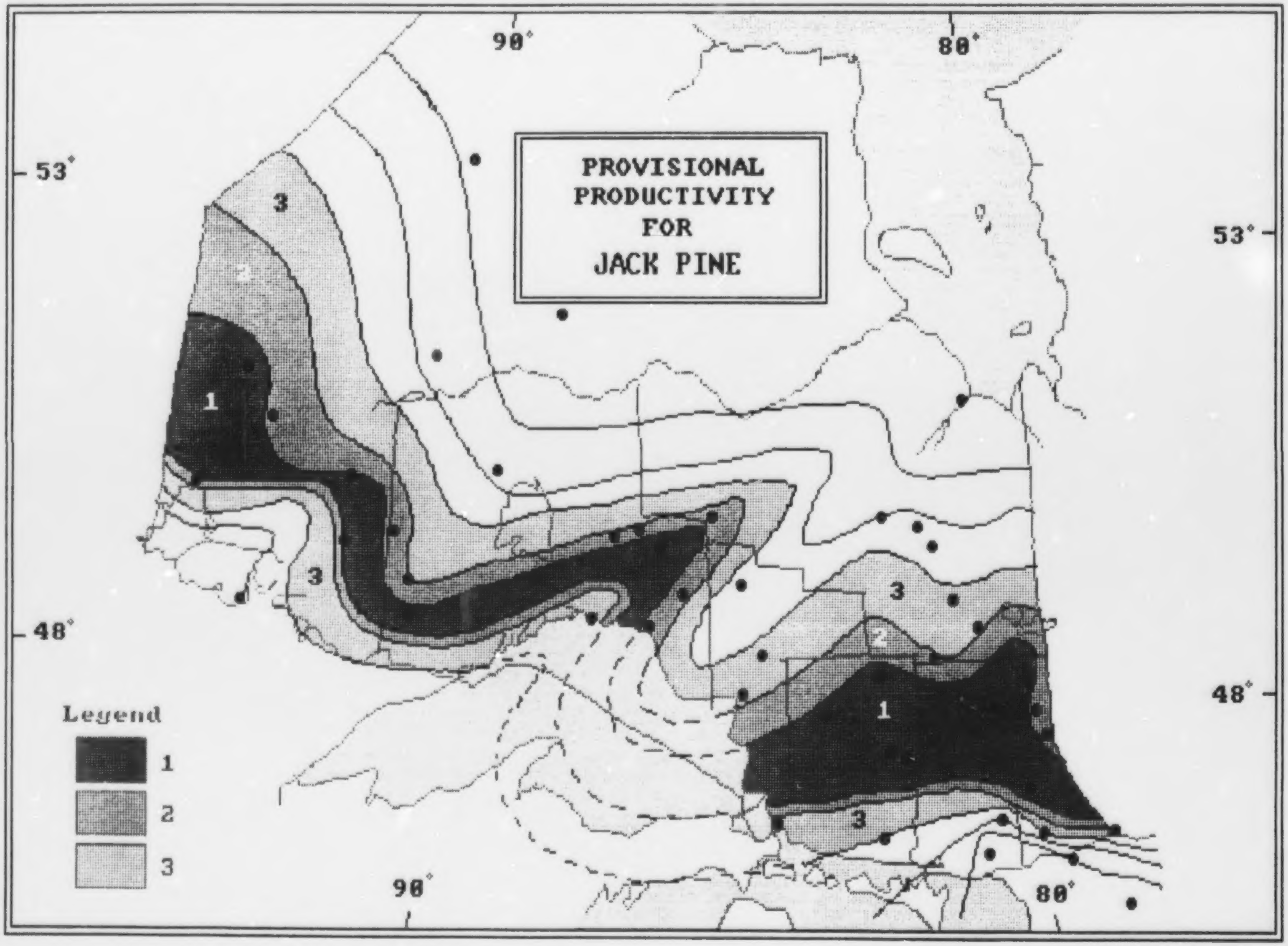

PROVISIONAL
PRODUCTIVITY
FOR
JACK PINE
90°
80°
53°
53°
48°
48°
90°
80°
1
2
3
3
3
1
2
3
3
Legend
1
2
3

FIG. 3. Provisional Productivity for Jack Pine

erate stand deterioration; contribute to the fuel loading for forest fires and increase the need for improved monitoring and suppression technology. However, forest managers can minimize this degree of growth slowdown during recurrent climate stress periods with timed stand tending operations with the expectation of superior growth recovery during subsequent balanced climate periods.

New preventive forest protection directions will focus on intensive and shorter rotations of genetically "resistant" species on climate sustainable sites. Under this management strategy, the definition of future climate envelopes by soil texture class for specific species is essential.

The higher investments required to establish and maintain these genetically improved forests could shift the priority for fire and other protection resources within the forest estate. For example, if the future climate change scenarios are realistic, rapid deterioration of the health and productivity of the old forest and greater fire losses can be expected. This poses an immediate threat to the new forest located in its midst and suggests a greater need for the partitioning of the forest land base.

Summary

Climate is a resource, and as a resource, it is now possible to calculate, based on the annual thermal and moisture stress, the annual volume slowdowns or accelerations within various regions by species. This has important implications for the evolution of the health and productivity of forest stands; annual allowable cut calculations; sensitivity to long-term climate change; and protection priorities.

References

FAYLE, D.C.F. AND D.C.MACIVER. 1986. Growth Layer analysis as a method for examining tree growth and development responses, pg. 40-48. In D.S. Solomon and T.B. Brann (Eds.) Environmental Influences on Tree and Stand Environment. I.U.F.R.O. Main Agr. Sep. Sta., University of Maine, Publ. 961.

Prédiction du rendement en matière ligneuse pour les peupleraies

J.-P. CARPENTIER
Ministère de l'Énergie et des Ressources
Sainte-Foy, Québec

Résumé

Au cours de l'année 1987, un modèle mathématique a été élaboré pour prédire l'évolution des composantes dendrométriques de tout peuplement composé principalement de peuplier fauxtremble. Pour qu'il soit utilisable sur l'ensemble du territoire forestier québécois, nous avons intégré dans l'algorithme de vieillissement des indices de densité et de qualité de station. Au niveau taxonomique, le modèle doit être classé dans la catégore appelée "Peuplement entier". Il est apte à considérer les peuplements équiennes et purs. De plus il est non spatial car il ne nécessite aucune information sur la localisation exacte de chacun des arbres; dans la littérature américaine ces modèles sont dits Distance Independent. Le module principal de vieillissement du modèle "PET" est un ensemble d'équations de régression non linéaires à variables explicatives multiples. Le modèle a comme but principal l'élaboration de tables de production avec ventilation diamétrale des quantités prédites sur une base quinquennale. L'estimation de l'âge d'exploitabilité absolu et de l'accroissement annuel moyen maximum est un sous-produit du modèle.

Abstract

During 1987, a mathematical model was developed that would predict changes in the dendrometric parameters of any stand composed principally of trembling aspen. To make the model useable throughout Quebec forests, density and station quality indicators were integrated into the aging algorithm. At the taxonomic level, the model belongs in the "whole stand" category. It is applicable to even-aged pure stands. It is also a non-spatial model in that it does not require any information on the precise location of each tree--what the US literature calls a "distance independent" model. The principal aging module of the model consists of a set of non-linear regression equations with multiple explanatory variables. The main output of the model is yield production tables, with quantities forecast by diameter on a five-year basis. As a byproduct, the model estimates the absolute rotation age and the maximum mean annual increment.

Introduction

Après le passage des feux de forêts on voit apparaître des peuplements pionniers. L'un des plus fréquents et des plus productifs est la tremblaie. On trouve ces peuplements dans pratiquement tout le Québec. Ils apparaissent sur une grande gamme de qualité de station. Les forestiers ont besoin de modèles mathématiques pour prévoir l'évolution et la croissance des peuplements. Les caractéristiques dendrométriques varient avec l'âge et elles sont particulières à une essence donnée.

En Ontario, Plonski (1974) a élaboré des tables de production normales. Il a construit des séries de croissance correspondant à des peuplements dont la densité etait optimale. Nous avons utilisé un échantillonnage systématiquement récolté. Nous avons calculé pour chancune des placettes des indices de qualité de station et de densité. Le logiciel de prédiction a été élaboré en tenant compte de ces indices. Il peut donc s'adapter à un large éventail de conditions initiales.

Un faisceau de courbes de hauteur en fonction de l'âge a été exprimé par une équation de régression non linéaire. L'ensemble des équations reliant les différentes variables dendrométriques forme le logiciel de prédiction "PET".

A partir de simulations réalisées grâce au logiciel "PET", on a réussi à calculer un âge d'exploitabilité absolu et l'accroissement annuel moyen maximum en se servant uniquement des indices de densité et de qualité de station comme variables explicatives. En connaissant la croissance et le rendement futur, on peut aménager avec rationnalité les richesses forestières.

Matériel et Méthode

CARACTÉRISTIQUES DES PLACETTES ÉCHANTILLONS

Les données de base proviennent du réseau provincial de placettes échantillons premanentes (P.E.P.). Le réseau est géré par le Service de l'inventaire forestier (S.I.F.) du ministère de l'Énergie et des Ressources (M.E.R.). Cent soixante-treize placettes ont été retenues pour établir le modèle de prédiction. Le tableau 1 renseigne sur différents attributs dendrométriques de l'échantillonnage de base. L'âge moyen se situe à 43 ans avec un écart type de 22. La placette la plus jeune avait 6 ans tandis que la plus vieille atteignait 158 ans.

DÉTERMINATION DE L'INDICE DE DENSITÉ (ID)

Dans le but de conceptualiser un modèle de prédiction à indice de densité variable, on en a calculé

Présenté au 10 ième Congrès sur les incedies et al météorologie Forestière les 17 au 24 avril 1989 à Ottawa, Canada.

Tableau 1. Principales statistiques des placettes échantillons pour le peuplier faux-tremble.

		Moyenne	Ecart Type	Minimum	Maximum
Age	:	43.4	22.0	6.2	158.0
Hauteur moyenne	:	15.1	4.8	3.7	28.1
Indice de qualite	:	17.5	3.3	10.4	25.6
Indice de densite	:	.88	.37	.50	2.38
Pourcentage de peuplier	:	75.2	13.9	50.1	100.0
Nombre total de tiges	:	2467	3056	225	16750
Nombre de tiges marchandes	:	658	385	0	2150
Surface terriere totale	:	17.79	6.36	3.30	32.99
Surface terriere marchande	:	14.60	8.80	.00	32.24
DHP moyen total	:	14.04	7.59	2.28	35.50
DHP moyen marchand	:	16.35	5.90	9.00	35.50
Volume marchand	:	100.81	83.03	.00	318.78

un dans chacune des placettes. Pour établir un niveau de référence, on s'est basé sur les données publiées par Plonski (1974) dans ses tables de production normales. On a effectué la régression du nombre de tiges en fonction du DPH moyen. On a recueilli les données des trois classes de qualité de station. L'équation suivante a été retenue comme étant valable dans les spectres d'âges et d'indices de qualité de station reconnus par Plonski.

$NCTP = b_0\ DHPMT^{b_1}\ b_2\ DHPMT$

$b_0 = 20289{,}231125$

$b_1 = -0{,}783197$

$b^2 = 0{,}966063$

D.L. = 48

R.M.S. = 3 955,843415

E.T.E. = 62,896

$R^2 = 0{,}996$

NCTP = Nombre calculé de tiges d'après Plonski
DHPMT = DHP moyen total en cm
D.L. = Degrès de libertè
R.M.S. = Moyenne des résidus quadratiques
E.T.E. = Ecart type de l'estimé
R^2 = Coefficient de détermination.

Nous définissons comme indice de densité (ID), le quotient du nombre réel de tiges totales (NRTT) par le nombre théorique de tiges (NCTP) calculé selon Plonski par l'équation précédente.

$$ID = \frac{NRTT}{NCTP}$$ où

NRTT = Nombre réel de tiges totales

ID = Indice de densité.

Nous avons ainsi calculé un indice de densité pour chacune des placettes et toutes celles ayant un indice inférieur à 0,50 ont été rejetées. L'indice de densité moyen pour l'ensemble des placettes acceptées est de 0,88. L'écart type est de 0,37 et l'indice maximal est 2,38. La répartition des placettes par classe de densité est montrée à la figure 1.

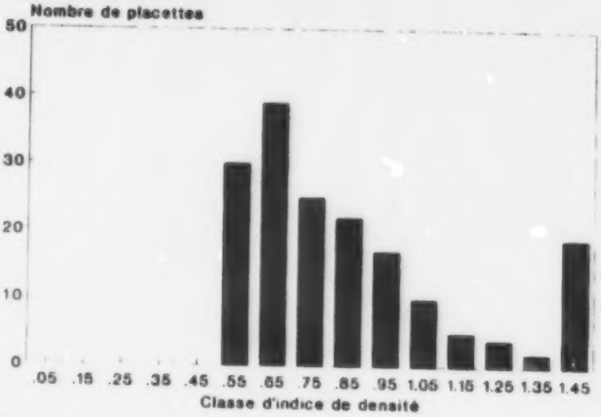


FIG 1. Distribution des placettes de peuplier faux-trembles selon l'indice de densité

DÉTERMINATION DE L'INDICE DE QUALITÉ DE STATION (IQS)

L'indice de qualité de station est le moyen utilisé par les dendrométriciens pour quantifier le potentiel de croissance d'un peuplement forestier. Cet indice intègre tous les facteurs génétiques d'une essence donnée, les facteurs pédologiques de la station et les facteurs microclimatiques régissant le lieu de croissance. Plutôt que d'estimer et de quantifier l'effet de chacun des facteurs, on se limite à constater leur influence globale. On l'estime à l'aide de l'âge moyen et de la hauteur moyenne des arbres dominants et codominants. Nous définissons précisément l'IQS comme étant la hauteur atteinte à l'âge de référence de 50 ans. Étant donné que très peu de placettes ont exactement 50 ans, nous avons besoin d'une équation d'estimation de l'indice de qualité. Dans Carpentier et al. (1989), on explique la procédure d'estimation des coefficients de l'équation de prédiction IQS = f(âge, H), en utilisant le modèle suivant:

$IQS = b_0\ H\ (1 - e^{b_1 Age})$

$b_0 = 0{,}729481$

$b_1 = 0{,}026265$

D.L. = 163

R.M.S. = 1,718

E.T.E. = 1,310738

$R^2 = 0{,}868$

IQS = Indice de qualité de station en mètres
H = Hauteur moyenne des dominants et des codominants.

On trouve à la figure 2 la distribution des placettes selon l'indice de qualité de station.

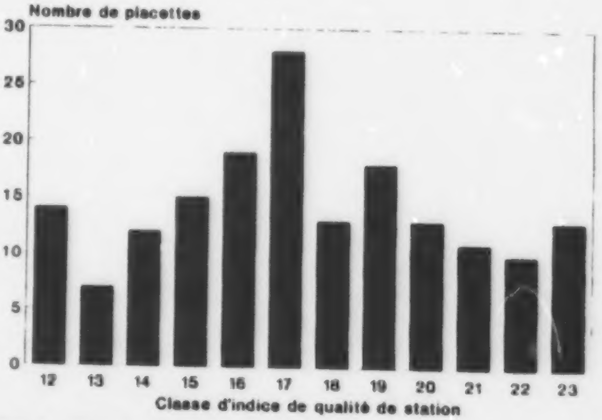


FIG 2. Distribution des placettes de peuplier faux-trembles selon l'indice de qualité de station

L'élaboration du modèle de prédiction nécessite l'estimation des hauteurs atteintes en fonction de l'âge. Sachant que ces hauteurs sont fonction de l'IQS, nous avons quantifié cette relation en nous servant des résultats de l'équation précédente. Pour la relation $H = f(\hat{A}ge, IQS)$, on utilise une équation de la forme: $H = a_0\ IQS\ (1 - e^{-a_1 \hat{A}ge})-1$.

Aucune régression n'est nécessaire pour trouver les coefficients a_0 et a_1, car un simple calcul mathématique démontre que:

$a_1 = b_1 = 0{,}729481$ $\quad$ $a_0 = 1/b_0 = 1{,}370836$

La figure 3 montre la hauteur en fonction de l'âge pour différents indices de qualité de station.

Résultats

PRÉDICTION DU VOLUME MARCHAND BRUT

Le volume marchand est fonction de la surface terrière marchande et de la hauteur moyenne prédite.

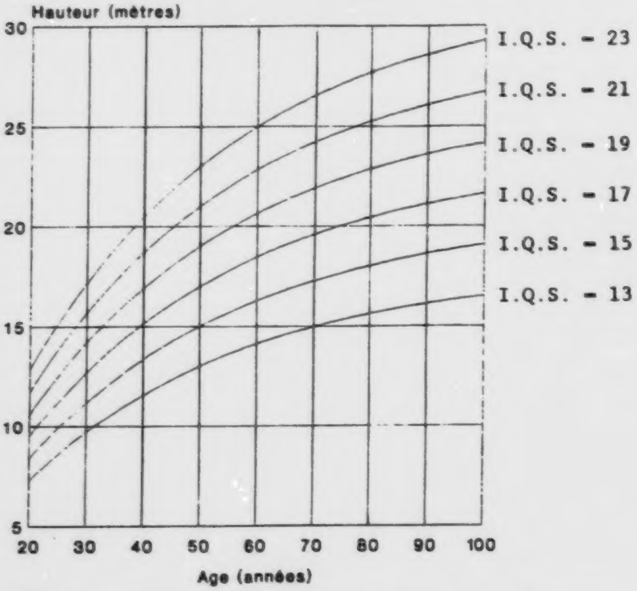


FIG 3. Hauteur moyenne en fonction de l'âge pour différents indices de qualité de station

La surface terrière marchande est reliée directement par une équation non linéaire avec la surface terrière totale. L'importance de l'IQS est mise en relief par le faisceau de courbes présenté à la figure 4. En effet, le volume est fortement influencé par la hauteur moyenne d'un peuplement. Nous avons vu précédemment que pour un âge donné, la hauteur augments avec l'IQS.

$VM = f(H, STM) = b_0\ H\ STM^{b_1}$ $\quad$ D.L. = 160

$b_0 = 0{,}26473$ $\quad$ E.T.E. = 10,95679

$b_1 = 1{,}13967$ $\quad$ R2 = 0,98

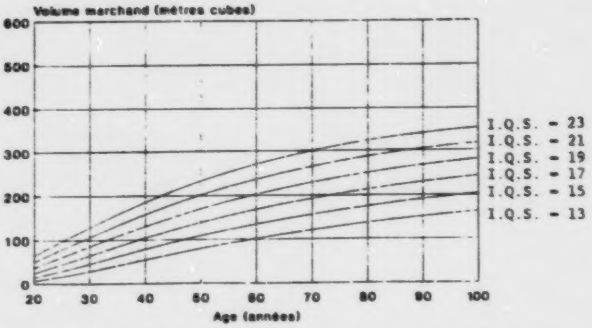


FIG 4. Volume prédit en fonction de l'âge par indice de qualité de station et pour l'indice de densité 0,8

AGE D'EXPLOITABILITÉ ABSOLU

En foresterie, il est de pratique normale de déterminer l'âge d'exploitabilité absolu d'un peuplement comme étant le point d'intersection de la courbe de l'accroissement annuel moyen et de celle de l'accroissement annuel courant. A cet âge, on retrouve également l'accroissement annuel moyen maximum. La figure 5 illustre l'âge d'exploitabilité absolu et l'accroissement annuel moyen maximum correspondant.

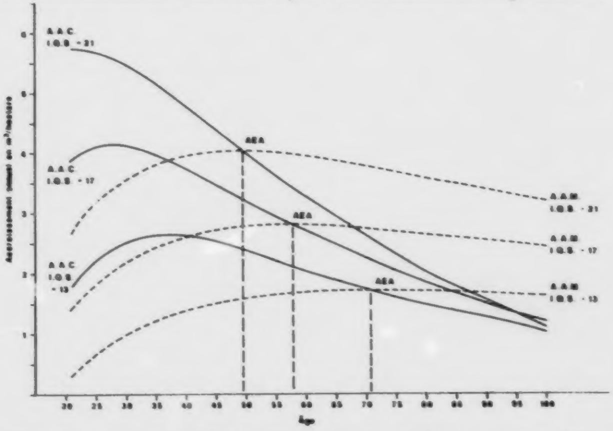


FIG 5. Age d'exploitabilité absolu (AEA) pour 3 IQS lorsque l'indice de densité est fixé à 0,8

De l'observation de cette figure, on constate que l'âge d'exploitabilité absolu (AEA) varie inversement en fonction de l'indice de qualité de station et que l'accroissement annuel moyen maximum (AAMM) croît avec l'indice de qualité de la station.

DISTRIBUTION DIAMÈTRALE DES TIGES

La réalisation de tables de distribution des tiges marchandes par classe de DHP permet aux aménagistes forestiers de mieux planifier l'exploitation forestière en ayant une meilleure connaissance de la dimension des bois disponibles au fil des années. L'équation de Weibull peut exprimer la distribution diamétrale en fonction du DHP. La fonction de densité de cette loi est être suffisamment souple pour permettre de représenter des courbes exponentielles, normales, voire même asymétriques Gamma. La fonction de densité (PDF) de la Weibull à trois paramètres s'énonce comme suit :

$$f_{w3}(x) = \begin{cases} \frac{\lambda}{\sigma}\left(\frac{x-\mu}{\sigma}\right)^{\lambda-1} e^{-\left(\frac{x-\mu}{\sigma}\right)^{\lambda}} \\ 0 \textit{ ailleurs} \end{cases} \qquad \lambda,\ \sigma,\ \mu > 0,\ x > \mu$$

où:

λ = Paramètre de forme
σ = Paramètre d'échelle
u = Paramètre de localisation
e = Base du logarithme népérien (2,718...).

Il a été démontré, selon Zutter el al. (1986a,b), que l'emploi d'une loi W_2, pour estimer les paramètres d'une distribution tronquée, est très acceptable. En suivant cette indication, nous avons régressé les paramètres lambda et sigma pour chacune des placettes. La technique du maximum de vraisemblance a été utilisée.

La fonction de distribution de Weibull a permis la réalisation de tables de distribution diamétrale. Ces tables permettent de mieux prévoir l'utilisation du bois pour les fins du sciage et du déroulage. Afin de rendre plus aisée la lecture du tableau 2, nous donnons la nomenclature suivante :

NTM = Nombre de tiges marchandes/ha (9 cm et +)
STM = Surface terrière marchande en m^2/ha
DHPM = Diamètre moyen quadratique en cm.

Les termes "réel" et de Weibull" sur le tableau 2 réfèrent au fait que le calcul est basé sur les classes prédites, on dit alors "réel", ou que le calcul est basé sur le modèle analytique, on dit à ce moment "de Weibull". En principe le calcul de Weibull serait plus exact car il n'y a pas de perte d'information numérique lors du calcul pour l'élaboration des tables.

CONCEPTION DE TABLES DE PRODUCTION

La fonction principale du modèle de prédiction "PET" est d'élaborer des tables de production devant prédire le rendement en volume de bois au cours d'un certain nombre d'années. Les tables peuvent être classifiées comme normales ou empiriques. En effet, ce modèle à indice de densité variable peut accepter comme intrant une variété de conditions initiales en termes de nombre de tiges par classe de diamètre et par hectare. Le modèle est également conçu pour s'adapter à toute la gamme des IQS observables dans les peuplements naturels de peupliers faux-trembles croissant au Québec. La période de prédiction s'étend de 20 à 100 ans. Il aurait été imprudent de dépasser ces limites car dans celles-ce, nous retrouvons plus de 89 p. 100 de notre échantillonnage.

COMPARAISON ENTRE LES PRÉDICTIONS DU MODÈLE "PET" ET LES TABLES DE PLONSKI

Il semble intéressant de comparer les résultats obtenus au Québec avec ceux publiés par Plonski (1974). Globalement, on doit constater que les peupleraies naturelles de l'Ontario sont plus productives que celles du Québec. On doit cependant noter qu'en Ontario, seules des stations bien stockées ont été échantillonnées. Ainsi, pour fins de comparaison, nous avons fixé l'indice de densité dans "PET" à 1.0. Il faut être très prudent lors de l'interprétation de la figure 6 car les volumes ont été calculés avec deux tarifs de cubage différents. De plus, au Québec, les volumes ne concernent que les tiges des peupliers; les tiges des autres essences ont été négligées.

Tableau 2. Table de distribution diamétrale des tiges pour le peuplier faux-tremble

AGE	NTM	STM	DH M	DISTRIBUTION DES TIGES PAR CLASSE DE DHP																STM	DHP M
	(	REEL M*2	CM	) 10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40+	(WEIBULL M*2	) CM
20	683	7.4	11.7	259	218	105	34	8	1	0	0	0	0	0	0	0	0	0	0	7.0	11.4
25	872	10.8	12.5	253	275	178	81	28	7	1	0	0	0	0	0	0	0	0	0	10.5	12.4
30	960	13.5	13.4	210	275	223	131	59	21	6	1	0	0	0	0	0	0	0	0	13.3	13.3
35	984	15.7	14.3	160	244	234	167	93	42	16	5	1	0	0	0	0	0	0	0	15.5	14.2
40	973	17.5	15.1	118	202	221	183	122	66	30	11	4	1	0	0	0	0	0	0	17.4	15.1
45	942	19.0	16.0	85	161	196	184	140	88	47	21	8	3	1	0	0	0	0	0	18.9	16.0
50	903	20.3	16.9	60	126	167	173	147	105	64	33	15	6	2	1	0	0	0	0	20.2	16.9
55	859	21.4	17.8	43	96	138	155	145	115	78	46	23	10	4	1	0	0	0	0	21.3	17.8
60	815	22.3	18.7	30	73	112	135	137	118	89	58	33	16	7	3	1	0	0	0	22.3	18.7
65	771	23.2	19.6	21	55	90	115	125	116	95	68	43	23	11	5	2	1	0	0	23.1	19.5
70	730	23.9	20.4	15	42	71	97	111	110	97	75	51	31	16	8	3	1	0	0	23.8	20.4
75	690	24.6	21.3	11	31	56	80	97	102	95	79	58	38	22	11	5	2	1	0	24.5	21.3
80	653	25.2	22.2	8	23	44	66	83	92	91	80	64	45	28	16	8	3	1	1	25.1	22.1
85	618	25.7	23.0	5	18	35	53	70	82	85	79	67	50	34	21	11	5	2	1	25.6	23.0
90	585	26.1	23.9	4	13	27	43	59	71	78	76	68	54	39	25	15	8	3	2	26.1	23.8
95	555	26.6	24.7	3	10	21	35	49	62	70	72	67	57	43	30	19	10	5	3	26.5	24.7
100	526	26.9	25.5	2	7	16	28	41	53	62	66	65	57	46	34	22	13	7	5	26.9	25.5

INDICE DE DENSITE = 0.80

INDICE DE QUALITE DE STATION = 17.0

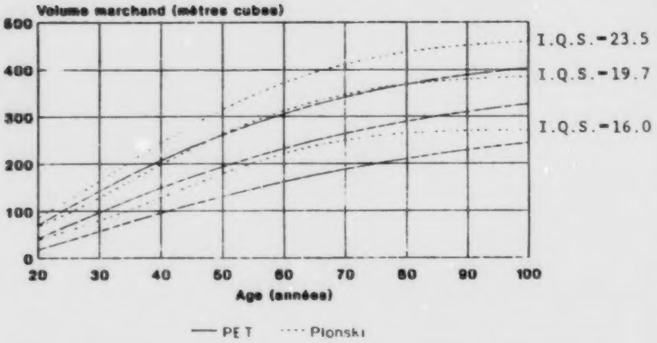


FIG 6. Volume marchant brut selon PET et Plonski par indice de qualité de station

COMPARAISON ENTRE LES PRÉDICTIONS DU MODÈLE "PET" ET CELLES DE PAGE ET VAN NOSTRAND

Â la section précédente, nous avons vu un schéma de croissance différent, pour le peuplier faux-tremble, entre la province de Québec et celle de l'Ontario. Nous sommes en droit de nous questionner si le même phénomène apparaît dans d'autres provinces voisines. C'est ainsi que nous avons retenu la province de Terre-Neuve comme seconde source de comparaison. A première vue, la figure 7 montre les peupleraies de Terre-Neuve plus productives que celles du Québec. Pour le modèle "PET", la croissance en volume se fait assez lentement contrairement à celle des tables de Page et Van Nostrand (1973).

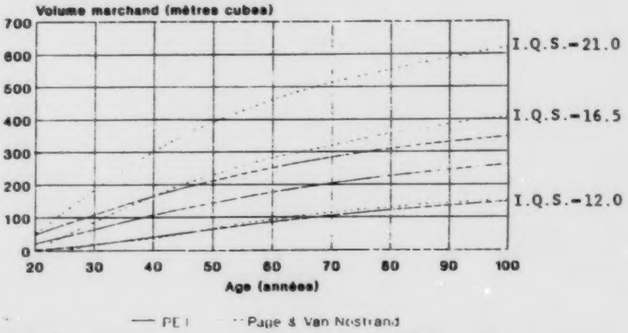


FIG 7. Volume marchant brut selon PET et Page et van Nostrand par indice de qualité de station

EVOLUTION DES VARIABLES DENDROMÉTRIQUES

La figure 8 montre l'évolution des composantes dendrométriques d'un peuplement. On constate que le nombre de tiges totales diminue en fonction du temps. Une partie des tiges mortes pourrait être récupérée en éclaircie. Il serait intéressant d'étudier différents scénarios d'éclaircie afin d'estimer le volume de récupération maximal. Quant au nombre de tiges marchandes, il augmente durant les premières années et

*Tableau 3 Table de production à densité variable

Age	Hauteur	N.T.T.	N.T.M.	S.T.T.	S.T.M.	DHPT	DHPM	Volume	Acc. Courant		Annuel Moyen	Age
	M			M*2	M*2	CM	CM	M*3	PC	M*3	M*3	
20	9.5	2352	683	12.4	7.4	8.2	11.7	25	----	----	1.23	20
25	11.2	1987	872	14.3	10.8	9.6	12 5	45	9.84	3.99	1.78	25
30	12.7	1720	960	16.0	13.5	10.9	13.4	65	6.79	4.16	2.18	30
35	14.0	1516	984	17.4	15.7	12.1	14.3	86	4.96	4.04	2.44	35
40	15.2	1354	973	18.8	17.5	13.3	15.1	105	3.79	3.82	2.62	40
45	16.2	1221	942	19.9	19.0	14.4	16.0	123	3.00	3.57	2.72	45
50	17.0	1110	903	21.0	20.3	15.5	16.9	139	2.44	3.32	2.78	50
55	17.8	1016	859	21.9	21.4	16.6	17.8	154	2.02	3.06	2.81	55
60	18.5	935	815	22.8	22.3	17.6	18.6	169	1.70	2.82	2.81	60
65	19.1	865	771	23.5	23.2	18.7	19.6	181	1.44	2.58	2.79	65
70	19.6	803	730	24.2	23.9	19.6	20.4	193	1.24	2.36	2.76	70
75	20.1	748	690	24.8	24.6	20.6	21.3	204	1.06	2.15	2.72	75
80	20.5	699	653	25.4	25.2	21.5	22.2	214	0.92	1.95	2.67	80
85	20.8	655	618	25.9	25.7	22.4	23.0	223	0.80	1.76	2.62	85
90	21.1	615	585	26.3	26.1	23.3	23.9	231	0.69	1.59	2.56	90
95	21.4	579	555	26.7	26.6	24.2	24.7	238	0.60	1.43	2.50	95
100	21.6	547	526	27.1	26.9	25.1	25.5	244	0.53	1.28	2.44	100

INDICE DE DENSITE = 0.80
ACCROISSMENT ANNUEL MOYEN MAXIMUM = 2.81
INDICE DE QUALITE DE STATION = 17.0
AGE D'EXPLOITABILITE ABSOLU = 58

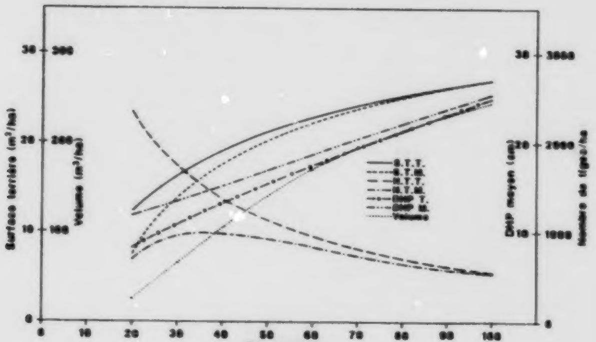


FIG 8. Évolution des variables dendrométriques en fonction de l'âge pour le peuplier faux-tremble. IQS = 17

diminue par la suite.

Les DHP moyens total et marchand, ser approchent à mesure que les années passent. Car la mortalité naturelle affecte principalement les étages inférieurs. La surface terrière est la variable dendrométrique qui intègre les effets des deux premières variables citées sur le rendement en matière ligneuse. On constate qu'elle tend vers une asymptote horizontale. Ceci s'explique par le fait qu'une station ne peut produire plus qu'un certain niveau.

PRÉCISION DU MODÈLE "PET"

A l'aide du réseau des placettes permanentes du MER, nous avons pu valider les prédictions du modèle "PET" en nous servant de 67 P.E.P. ayant deux mesures. En prenant les mesures initiales des placettes, en les soumettant à "PET", puis en comparant les résultats calculés à l'aide du simulateur avec les secondes mesures, nous avons pu obtenir les résultats suivants présentés au tableau 4.

Nous constatons au tableau 4 que le volume semble difficile à prédire en bas âge. Ceci n'est guère surprenant pour les spécialistes en modélisation, car il est connu que des écarts sont fréquents dans les extrémités des régressions. Toutefois le modèle semble très précis en ce qui a trait au rest de la gamme des âges pour les différentes variables dendrométriques retenues.

Discussion

Les prédictions résultant de l'exécution du logiciel "PET" ont démontré que son élaboration reposait sur des principes logiques. Une méthodologie d'établissement de séries de croissance temporelle à partir d'observations poncturelles a été utilisée. Elle a été vérifiée grâce aux 43 placettes échantillons mesurées deux fois. L'élaboration du logiciel a reposé également sur deux postulats jusqu'à maintenant acceptés. L'indice de qualité de station ne varie pas dans le temps au cours du développement d'une génération d'arbres. L'indice de densité est également stable sauf lors de perturbations graves. Le logiciel n'a pas été conçu pour en prévoir l'occurrence, ni pour évaluer les pertes occasionnées par de tels événements.

Le logiciel de prédiction est moins fiable dans des situations extrèmes de qualité de station, de densité et d'âge. Il faut être prudent dans ces cas limites. Dans quelques années, les données de base seront plus abondantes, et on devrait étudier en détail les cas extrèmes, en particulier l'évolution des vieilles peupleraies. Il est possible que des placettes disparaissent de l'échantillonnage de base lorsque la proportion de tiges de peupliers devient trop faible. A ce moment, les autres essences devenant relativement plus important, des parcelles peuvent avoir été rejetées. Il est possible qu'un recrutement de placettes avec un taux d'importance relative en peuplier variant avec l'âge des placettes ait résolu le problème.

Tableau 4. Vérification du modèle "PET" pour des prédictions stratifiées par classes d'âge pour le volume marchand brut en
mètres cubes

Classe d'age	Nombre placette	Volume Reel Init.	Final	Δ	Volume Calcule init.	Final	Δ	Volume Predit	Ecart	Precision
20	4	0	1	1	2	8	6	6	5	.0
30	14	35	73	38	47	93	46	81	9	88.1
40	12	66	95	29	85	116	32	98	2	97.5
50	16	101	125	24	96	122	26	127	2	98.1
60	9	123	143	20	117	145	28	151	8	94.5
70	8	173	209	36	160	199	39	212	3	98.6
80	4	263	301	37	244	278	35	298	-3	99.0
TOTAL	67	96	124	28	97	130	33	129	4	96.5

Bibliographie

CARPENTIER, J.-P., L. LACOMBE et P. TARDIF. 1989. Modélisation de la croissance et du rendement des peuplements de peuplier faux-tremble au Québec. Serv. de la rech. appl., Min. de l'Énerg. et des Ress., Québec. 227 p.

PAGE, G. et R.S. VAN NOSTRAND. 1973. Empirical yield tables for the major forest cover types of Newfoundland. Can. For. Serv., Nfld. Inf. Rep. N-X-100. 84 p.

PERRON, J.-Y. 1983. Tarif de cubage général. Volume marchand brut. Serv. de l'inventaire forestier. Min. de l'Énerg. et des Ress., Québec.

PLONSKI, W.L. 1974. Normal yield tables (metric) for major forest species of Ontario. Ministry of Natural Resources, Div. For., Toronto, Ontario. 40 p.

ZUTTER, B.R., R.G. ODERWARLD, P.A. MURPHY and R.M. FARRAR. 1986a. Characterizing diameter distributions with modified data types and forms of the Weibull distribution. For. Sci. 32(1): 37-48.

ZUTTER, B.R., R.G. ODERWARLD, P.A. MURPHY and R.M. FARRAR. 1986b. Characterizing diameter distributions with modified data types and forms of the Weibull distribution. For. Sci. 32(1): 37-48.

Prediction of Crown Fire Behavior in Conifer Stands

C.E. VAN WAGNER
Research Scientist
Forestry Canada
Petawawa National Forestry Institute
Chalk River, Ontario

Abstract

A scheme is presented for dealing with the full range of fire behavior in conifer forests. It is based on empirical data from fires in Canadian forests plus a theory to describe the physical conditions for the transition from surface to crown fire. In its ideal form, the model consists of two distinct equations for spread rate in a given forest, one each for surface and crown fire, plus the rules for the transition upward or downward between them. For lack of enough data in some cases, a compromise has been devised that distinguishes between surface and crown fires, but does not provide for complete separation of the spread-rate functions. The scheme will form part of the forthcoming Canadian Forest Fire Behavior Prediction (FBP) system.

Résumé

Nous vous présentons une méthode pour faire face à toute la gamme de comportement du feu dans des forêts de conifères. Elle repose sur des données empiriques compilées lors d'incendies forestiers survenus au Canada ainsi que sur une théorie décrivant les conditions physiques de la transition entre un feu de surface et un feu de cime. Le modèle, dans sa forme idéale, comporte deux équations distinctes sur la vitesse de propagation dans une forêt donnée, l'une pour un feu de surface et l'autre pour un feu de cime ainsi que les règles pour calculer la transition entre eux vers le haut ou vers le bas. Compte tenu de l'insuffisance de données dans certain cas, nous avons trouvé une solution intermédiaire qui établit une distinction entre le feu de surface et le feu de cime, mais qui ne permet pas une séparation totale des fonctions de vitesse de propagation. La méthode fera partie de la Méthode canadienne de prévision du comportement des incendies de forêt qui va bientôt être rendue publique.

Introduction

The prediction of forest fire behavior in Canada is accomplished through the Canadian Forest Fire Behavior Prediction (FBP) System, a division of the larger Canadian Forest Fire Danger Rating System (Canadian Forestry Service 1987, Stocks et al. 1989). The preliminary guide to the FBP System (Alexander et al. 1984) presented, among other things, spread-rate equations for 14 forest or fuel types throughout Canada, all based on the Initial Spread Index (ISI), a component of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987), another division of the larger Danger Rating System mentioned above.

At the Eighth Conference in this series, Lawson et al. (1985) described the preliminary version of the FBP System, including its database (now about 360 fires), and covered the general approach to its development.

Since 1984 a more complete version has been under development, which is expected to appear shortly. The purpose of the present paper is to describe the design and structure of the section dealing with fire behavior in conifer stands, especially the transition from surface to crown fire and the distinction between the two.

In the original work on the FBP, the conifer data numbered some 160 fires, both wild and experimental, about half of them crown fires. These were sorted and assigned to seven different conifer forest types and graphed against the ISI. The typical pattern was best suited with the type equation

$$ROS = a(1 - e^{-bISI})^{c} \qquad (1)$$

where ROS is spread rate, ISI is Initial Spread Index, and a, b, and c are constants for the fuel type. As described by Lawson et al. (1985), this equation produces an S-shaped curve whose lower section (at low ISI) represents surface fires, the upper flattening section (at high ISI) represents crown fires, and the steep intermediate section a transition zone.

A modern system for explaining and predicting fire behavior in conifer forest should, in addition, account for

- the effect of variable fuel consumption on spread rate,

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

- fuel consumption itself, to permit computation of intensity,
- the transition from surface to crown, and
- the behavior of the crown fire.

The "ideal" crown fire model should comprise separate equations for surface and crown fire spread, plus the rules for transition upwards or downwards between them. It might also include means of varying the stand height and stand density. Such a nearly complete model has been designed for one conifer type, namely red pine plantation. For the others, however, a compromise has been adopted. The single ISI-based equation for the full range of behavior is retained, but the model provides some variation about the basic equation plus an estimate of the degree of crown engagement.

A full account of the entire new FBP System, with all equations and rules for procedure will eventually be published elsewhere. So, because the scope of this paper is limited to fire in conifer forest, some subsidiary sections of the whole system will be here described in brief only. A list of the symbols used appears at the end of the text.

Model Structure

I FUEL-WEIGHT EFFECT ON SPREAD RATE

The first new problem to be addressed was the effect of fuel weight on surface spread. Because the ISI is based on the Fine Fuel Moisture Code (FFMC) whose timelag in practice is only a day or so, the computed spread rates would apparently apply in given daily weather regardless of the further length of time since heavy rain. The primary indicator of available fuel weight in the FWI System is the Buildup Index (BUI), whose practical timelag extends to two weeks or so.

Although the correlations of spread rate with ISI were generally very good, no amount of statistical analysis could show any secondary dependence of spread rate on the BUI. In fact, given the empirical nature of the fire data, collected without specific concern for the full range of BUI, it was probably unreasonable to expect anything more than a good correlation with the primary variable. Nevertheless, because all physical logic points to a real effect of available fuel weight on the spread rate, and to avoid over-estimating spread rate very soon after rain, it was decided to include a BUI function, called f(U), as a modifier to the main ISI-based equation. It is based on the assumption that spread rate must be zero at BUI zero, rise quickly with increasing BUI, then finally level off at a maximum for the given value of ISI. Here is a brief description of the result:

First, the assumption above was expressed as

$$f(U) = f(U_m)e^{-a/U} \qquad (2)$$

where U is BUI and U_m is BUI_m. The concept "q" was then introduced, defined as the proportion of maximum possible spread rate (for a given ISI) that is reached at a standard BUI called U_s. Somewhat subjectively, each fuel type was assigned a q-value, ranging from 0.70 to 1.00 depending on the rate at which dryness in depth might affect spread rate. But the fires within each fuel-type data set have their own particular average BUI, to which the empirical ISI-based spread equation should presumably best apply; at such a value, called U_o, f(U) should equal 1. Several algebraic steps then produced the equation

$$f(U) = \mathrm{Exp}\ [U_s \ln q\ (1/U - 1/U_o)] \qquad (3)$$

The values of q and U_o are listed for each fuel type, and the normal standard BUI was set at 50. The function f(U) could then be readily calculated for any BUI and applied as a multiplier on the result of the basic ISI spread equation. Three examples are shown in Figure 1.

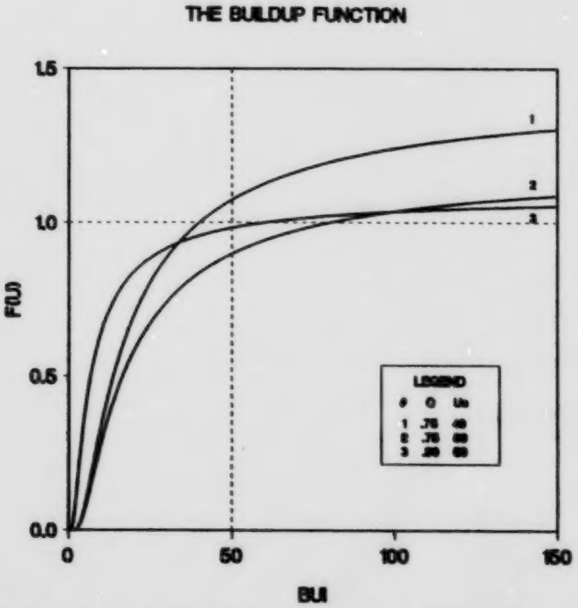


FIG 1. Graphs illustrating the form of the Buildup Function, f(U), at three combinations of q and U_o. f(U) = 1 when BUI = U_o. Also U_s = 50.

II FOLIAR MOISTURE CONTENT

Foliar Moisture Content (FMC) has an important bearing on two features of the fire behavior model, namely the initiation of crowning and the crown spread rate. Because it is out of the question to require every region to be continuously aware of the current FMCs in its conifer forests, a scheme was required for estimating FMC on demand from simple information such as location and date.

The basis of the scheme is the known seasonal variation in the FMC of old conifer foliage, especially a period of relatively low values in the spring and early summer, referred to here as the "spring dip". Its mechanism is mainly physiological, being due rather to a temporary increase in dry weight than to a real decrease in cellular water content (Little 1970, Gary 1971). For practical purposes, it was therefore assumed that its date is fairly constant from year to year, and not much affected by annual trends of soil and air temperature.

As field data for the scheme, nine Canadian foliar-moisture trends were available, ranging in location from longitude 67° to 124°, and as far north as latitude 59°. A more complete account of its design and structure will be published elsewhere, but the main steps were, in brief, as follows.

1) A "standard spring dip" was designed in terms of duration and amplitude, to represent all conifer species. It is constructed of two linked parabolas, and the limiting values are 85% and 120%. Given the date of its minimum plus the date of the fire in question, an FMC could then be estimated.

2) Analysis of the dates of minimum FMC, namely DO, among the nine sources eventually yielded a model in terms of latitude, longitude, and elevation. The key to this analysis was that, according to the nature of climatic isotherms in Canada, the isoline for a given DO should form a curve of decreasing slope from northwestern Canada, gradually becoming parallel to latitude in the east. The final equation for DO is thus a semilog function of longitude, plus normalizing functions to accommodate elevation and latitude.

The FMC for any hypothetical fire can now be estimated entirely from its location, elevation, and date. It is then used as required in further sections of the crown fire model.

III CRITERION FOR THE START OF CROWNING

As spread rate increases, a point is eventually reached at which the crowns become engaged. In the new FBP System this point is judged by the intensity criterion of Van Wagner (1977), namely his Equation (4), which defines the critical surface intensity for crowning in terms of the Crown Base Height (CBH) and the Foliar Moisture Content (FMC). Called CSI, it is given in terms of the FBP symbols as

$$\mathrm{CSI} = 0.001\,(\mathrm{CBH})^{1.5}\,(460 + 25.9\mathrm{FMC})^{1.5} \qquad (4)$$

Next, a prediction of the actual surface frontal intensity was needed. The function for spread rate has already been covered, and equations for Surface Fuel Consumption (SFC) based on correlation with the BUI for the individual fuel types have been developed. Assigning a constant 18 000 kJ/kg for heat of combustion, surface frontal intensity (SFI) is then given by

$$\mathrm{SFI} = 300\ \mathrm{RSS} \times \mathrm{SFC} \qquad (5)$$

where SFI is in kW/m, RSS is surface spread rate in m/min, and SFC is in kg/m^2. SFI and CSI are then compared. If SFI is the lesser, the fire is classed as Surface; if SFI is the greater, then as Crown, and the computation proceeds to the next step.

It is obvious that the Crown Base Height (CBH) is a critical factor in the crowning criterion. Because the theory on which the criterion is based was itself dependent on empirical data for its final form, it was inevitable that the CBH assigned to each fuel type description incorporates some indication of CBH; on the other hand, the assigned value had to match the general crowning pattern embedded in each fuel type's data set. The final assigned CBHs, with this reservation, represent the real forest structure as well as possible.

IV TRANSITION FROM SURFACE TO CROWN

Although a given surface fire when, say, the wind increases, may appear to rise quickly into the crowns and assume more or less instantly a new high-intensity state, there are two reasons for adopting a gradual transition for purposes of the FBP System.

First, wind in the FWI System is single-valued, whereas in reality it varies erratically around its mean. This means that within a certain range of mean wind speeds, the fire should be alternately on the surface during the lulls and in the crowns during the gusts, on a scale of a few minutes. In this state, it would presumably spread at a rate between that of pure surface and pure crown fire. Such behavior may indeed be observed on occasion. The second argument is statistical. With all the variability in fuel type, plus the inaccuracies in any empirical data set, it seemed safer to attempt prediction of a degree of crowning than to try to identify each fire as pure Surface or pure Crown.

Accordingly, a transition function was designed to accomplish this concept. It was assumed that the degree of crowning would depend on the amount by which the predicted surface intensity (SFI) exceeded the critical intensity (CSI). In practice, the concept is more easily handled in terms of spread rate; in other works, the amount by which the predicted surface spread rate (RSS) exceeded the spread rate (RSO) associated with the critical intensity. The practical yardstick chosen was that crowning should be 90% complete when (RSS) exceeded (RSO) by 10 m/min.

First, RSO is readily found by putting CSI for SFI in (5) and working backwards. The desired transition function, called the Crown Fraction Burned (CFB) becomes, then,

$$\mathrm{CFB} = 1 - \mathrm{Exp}[-a(\mathrm{RSS} - \mathrm{RSO})] \qquad (6)$$

where a = 0.23 in order to accomplish the transition at the rate specified above. This function is applied in determining both the resultant crown-fire spread rate and the degree of crown consumption, leading finally to the frontal fire intensity.

Two different models of crown-fire behavior are used in the new FBP System. Before presenting them, however, the role of foliar moisture content is first described.

V FOLIAR MOISTURE EFFECT

Foliar Moisture Content (FMC) has already appeared as part of the criterion for judging the onset of crown ignition (Section III). By physical logic, it must also have some effect on the rate of fire spread through the crown layer. Because FMC in Canadian conifer forest exhibits a strong seasonal trend (e.g., Van Wagner 1967), with distinctly lower values during spring, the implication is that crown fires should start more easily and spread faster during that season. Again, as with the BUI effect, analysis of the fire data failed to yield any statistical evidence, probably owing to the various empirical limitations in the data. The physical argument was then applied, as adapted for crown fire by Van Wagner (1974) from original arguments by Thomas et al. (1964), that spread rate should be

a) proportional to the horizontal radiant heat flux through the crown layer
b) inversely proportional to the foliar ignition energy, and
c) inversely proportional to the foliar bulk density.

The effect of seasonal variation in foliar bulk density was omitted as a conservative simplification, leaving the first and second effects to be accounted for. Expressions for crown flame temperature T and heat of ignition h, both in terms of FMC, were first required. A reasonable expression for the first is

$$T = 1500 - 2.75(\mathrm{FMC}),\ \text{in °K}, \qquad (7)$$

based on an assumed air supply twice that needed for perfect combustion[1], and for the second,

$$h = 460 + 25.9(\mathrm{FMC}),\ \text{in kJ/kg}, \qquad (8)$$

taken from Van Wagner (1977). Applying Boltzmann's fourth-power law of thermal radiation, and adjusting decimal points for convenience, the desired Foliar Moisture Effect (FME) is given by

$$\mathrm{FME} = 1000\,(1.5 - 0.00275\mathrm{FMC})^4/(460 + 25.9\mathrm{FMC}) \qquad (9)$$

It must be quickly explained that the FME is always applied in ratio with a normal value FME_o, which is based on the supposed average FMC (namely, 97%) found in the composite crown-fire data set. Therefore, a real proportionality constant is not required. The value of FME_o is 0.778. In practice, FME varies from 0.525 to 0.966 within the standard FMC range of 85% to 120%.

VI TWO-EQUATION CROWN FIRE MODEL

Ideally, it was supposed, any fire in a conifer stand could be visualized mathematically as some point in the space between two bounding curves, a lower one representing pure surface fire and an upper one representing complete crown engagement. This concept is most readily handled in terms of spread rate as dependent primarily on the ISI. Then, if SFI exceeds CSI (see Section III), crown ignition is assumed. The process of determining the final spread rate is best described with the help of a diagram.

In Figure 2, the lower curve represents all possible surface fires, with spread rate RSS; the upper curve represents complete crown fires with spread rate RSC. Obviously, the right end of the RSS curve and the left end of the RSC curve never come into play, but a central range of horizontal overlap does exist, depending on the secondary effects of BUI (Section I) and FMC (Section IV).

The horizontal dashed line in Figure 2 represents RSO, the critical spread rate at which crowning begins. The value of CFB, the Crown Fraction Burned, is first computed (see Section III) from the difference between

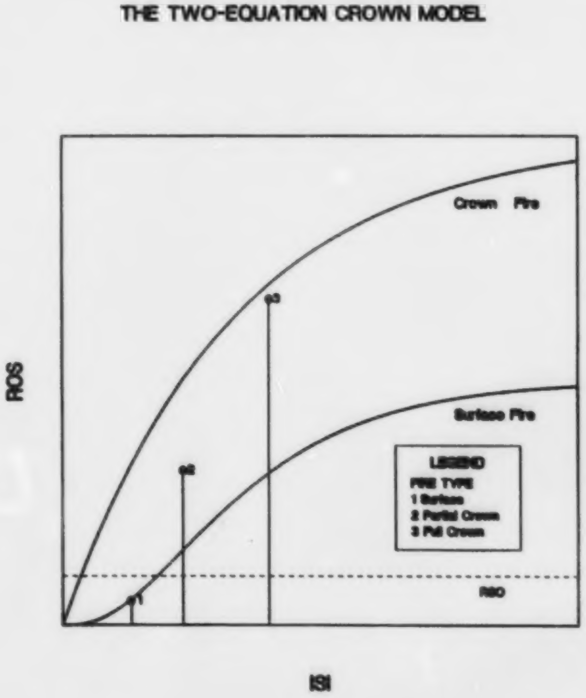


FIG 2. Graph of the two-equation crown-fire model, including a) separate curves of spread rate for surface and crown fires, b) a horizontal line representing RSO, the critical spread rate, and c) three examples of final spread rate.

RSS and RSO. The resultant final spread rate ROS is then found from

$$ROS = RSS + CFB\,(RSC - RSS) \qquad (10)$$

In other words, the amount by which the spread rate rises above RSS depends on the amount by which RSS exceeds RSO; the intermediate function is the CFB. This latter factor is also applied to the Crown Fuel Load CFL to obtain the actual Crown Fuel Consumption CFC. The Frontal Fire Intensity FFI can now be determined.

The crowning process assumed by this model can be further visualized by imagining that the tendency of the crown fire to attain its full potential is somehow hampered by the restraining action of the surface phase as measured by the CFB. With secondary effects operating, actual crown fires will occupy a band of space rising to the right from the region where RSS first exceeds RSO to meet the RSC curve at ISI's high enough to produce full crowning.

Three examples appear in Figure 2. At ISI$_1$, the surface spread rate RSS lies below the critical rate for crowning RSO; the fire therefore remains on the surface. At ISI$_2$, RSS exceeds RSO, so the fire crowns, the CFB is appreciable, and the final ROS is somewhere between RSS and RSC. At ISI$_3$, the RSS is high enough that CFB approaches 1 and the fire spreads nearly at the RSC value.

The flexibility of this two-equation model allows for variation in the Crown Base Height (CBH) as it depends on stand height. This feature is particularly desirable for intimately-known areas of flammable plantation forest.

VII SINGLE-EQUATION CROWN FIRE MODEL

For most conifer fuel types, including the major boreal species, it was decided to retain the full-range spread-rate equation, and to design a less complete model around it (see Fig. 3).

A spreadrate is first computed from the basic equation and labelled temporarily RSS, as for surface fire. The routine for judging the onset of crowning (see Section II) is called into play and, if RSS exceeds RSO, the fire is labelled Crown; the Crown Fraction Burned (CFB) is then computed (see Section IV).

From the region where crowning begins, the basic curve is then assumed to occupy a vertical range whose upper bound represents fires spreading at minimum FMC, and whose lower bound the case of maximum FMC. The CFB determines the extent to which the predicted resultant ROS departs from the basic curve toward the upper or lower bound. The process is normalized, as before, to the supposed mean FMC of the composite crown-fire data set. The resulting equation for final spread rate is, accordingly,

$$ROS = RSS\,[1 + CFB(1.285FME - 1)], \qquad (11)$$

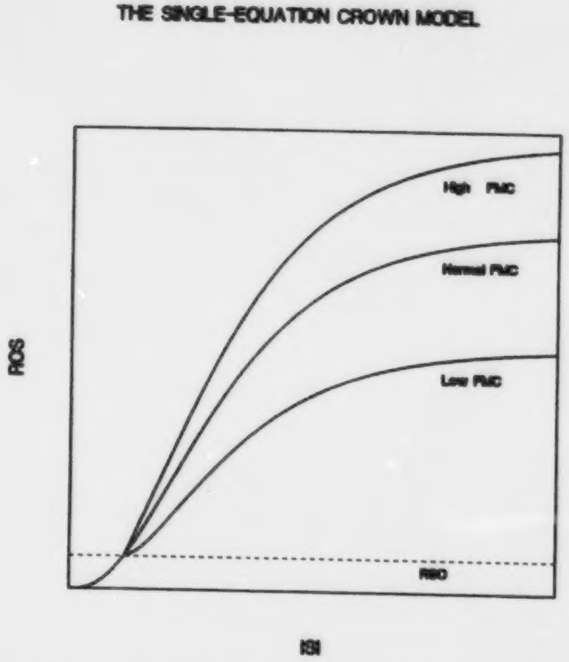


FIG 3. Graphs of the single-equation crown-fire model, built around the standard equation for normal FMC. The curves for high and low FMC start at RSO, the critical spread-rate for crowning. They represent the upper and lower limits of FMC within the standard spring dip.

where 1.285 is the above-mentioned normalizing factor. Thus, if 1.285FME exceeds 1, the fire spreads faster than the basic curve value and vice versa. Because CFB starts at zero just at the point where crowning is first possible, the effect of (11) is to produce a gradually widening band of potential fires that reaches its greatest width as CFB approaches 1.

As before, the CFB is applied to the full Crown Fuel Load (CFL) to yield the actual Crown Fuel Consumption (CFC), permitting a computation of final Frontal Fire Intensity (FFI).

The single-equation model provides for the identification of fires as Surface and Crown, and provides for some variation in spread rate and intensity.

Conclusion

As with previous work in Canadian forest fire danger rating, the present fire behavior model is an obvious blend of empirical data and physical theory. Because crown fire looms so large in the Canadian forest-fire scene, the model must account for it as logically as possible. But the complete combustion process in heterogeneous natural fuel, especially in distinct surface and crown layers, has so far proven intractable by physics and mathematics alone. The model of Albini and Stocks (1986) has come closest but is not yet in practical form. At the same time, the available empirical data are still not robust enough to demonstrate statistical evidence of several effects that must, by force of physical logic and indirect evidence, play some part in real fire behavior. Thus the compromise between theory and field data as described previously.

A particular issue is the basic label, Surface or Crown, applied to each fire. At present, only fires whose SFI is less than CSI are classed as Surface; a fire with any degree of crown engagement, no matter how small, is labelled Crown. Van Wagner (1977) classed crown fires as passive, active, or independent, each with a somewhat different mechanism. The crown-fire models described here will, however, not accommodate such distinctions; perhaps some classification according to CFB can be developed.

Failing statistical evidence for each distinct effect or factor, the best evidence of the new FBP System's credibility must lie in its ability to predict overall fire behavior. Again there is difficulty, because every available documented fire has already been used in deriving the basic empirical rates of spread and fuel consumption. The model can thus be "verified" against its own design data, but not yet "validated" against independent data. In fact, the average R-squares for regressions of predicted behavior vs. observed were as follows:

- for spread rate, 0.82,
- for fuel consumption, 0.36,
- for frontal fire intensity, 0.61

Of these 160 conifer fires, 82 were listed as Surface in the original data set, the other 78 as Crown. The model's predictions as to fire type were correct in 144 (or 90%) of cases.

As time passes, new fire data will become available, and weaknesses in the new FBP System will be exposed. Periodic modifications are to be expected. Meanwhile, for the first time, a more or less comprehensive model of fire behavior in Canadian forests is at the point of release for use in forest fire management.

List of Symbols

FWI - Fire Weather Index (System)
FBP - Fire Behavior Prediction (System)
ISI - Initial Spread Index
BUI - Buildup Index

f(U) - BUI function
U_s - Standard BUI
U_a - Average BUI for a fuel type
q - Factor representing fuel buildup with dryness in depth

FMC - Foliar Moisture Content
FME - Foliar Moisture Effect
DO - Date of minimum FMC
CBH - Crown Base Height
CFB - Crown Fraction Burned

ROS - Final spread rate
RSO - Critical spread rate
RSS - Surface spread rate
RSC - Crown spread rate

SFC - Surface Fuel Consumption
CFL - Crown Fuel Load
CFC - Surface Fuel Consumption

SFI - Surface intensity
CSI - Critical Surface Intensity
FFI - Frontal Fire Intensity

Endnotes

[1] From an unpublished report on file at the Petawawa National Forestry Institute by C.E. Van Wagner.

References

ALBINI, F.A. and B.J. STOCKS. 1986. Predicted and observed rates of spread of crown fires in immature jack pine. Combust. Sci. and Tech., 48(1):65-76.

ALEXANDER, M.E., B.D. LAWSON, B.J. STOCKS and C.E. VAN WAGNER. 1984. User Guide to the Canadian Forest Fire behavior Prediction System. Interim ed. Can. For Serv.

CANADIAN FORESTRY SERVICE. 1987. Canadian Forest Fire Danger Rating System - User's Guide. Three-ring binder (unnumbered publication).

GARY, H.L. 1971. Seasonal and diurnal changes in moisture contents and water deficits of Engelmann spruce needles. Bot. Gaz. 132(4):327-332.

LAWSON, B.D., B.J. STOCKS, M.E. ALEXANDER and C.E. VAN WAGNER. 1985. A system for predicting fire behavior in Canadian forests. Pp. 6-16. In Proc. Eighth Conf. Fire and Forest Meteorol., Soc. Am. Foresters, Bethesda, MD.

LITTLE, C.H.A. 1970. Seasonal changes in carbohydrate and moisture content of well-watered conifers. Bot. Gaz. 128:179-185.

STOCKS, B.J., B.D. LAWSON, M.E. ALEXANDER, C.E. VAN WAGNER, R.S. MCALPINE, T.J. LYNHAM, AND D.E. DUBÉ. 1989. The Canadian Forest Fire Danger Rating System: an overview. For. Chron. 65(6): 450-457.

THOMAS, P.H., D.L. SIMMS and H.G.H. WRAIGHT. 1964. Fire spread in wooden cribs. Joint Fire Res. Org. Fire Res. Note 537. Boreham Wood, U.K.

VAN WAGNER, C.E. 1967. Seasonal variation in moisture content of eastern Canadian tree foliage and the possible effect on crown fires. Can. Dep. For. and Rural Develop. Dep. Pub. 1204.

VAN WAGNER, C.E. 1974. A spread index for crown fires in spring. Can. For. Serv. Inf. Rep. PS-X-55.

VAN WAGNER, C.E. 1977. Conditions for the start and spread of crown fire. Can. J. For. Res. 7(1):23-34.

VAN WAGNER, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Can. For. Serv., Ottawa. For. Tech. Rep. 35.

A Weather-Based Fire Season Model

A.J. SIMARD
J.E. EENIGENBURG
W.A. MAIN
USDA Forest Service
North Central Forest Experiment Station
East Lansing, Michigan

Abstract

The occurrence of green-up and consequent reduced fire activity is obvious to local fire managers. It is less obvious, however, at regional and national scales. Also, the impact of drought on live fuel phenology is poorly understood. Finally, phenological data are generally not available to researchers analyzing historical weather data bases. This paper describes a weather-driven model that tracks the impact of green-up on wildland fire severity.

We obtained 20 years of daily weather data for 148 National Weather Service stations in all 50 States. These were paired with 15 years of computerized fire data from 100 National Forests. We also used 18 months of weather data from 600 stations from across the country in conjunction with 700 large fires (500+ acres) occurring in 34 States.

Development started with an unpublished herbaceous stage model developed by Keetch in 1971. His station code tables, originally intended for the eastern US, were extended to broaden the range of applicability. We added an elevation component to the station code calculation - an essential feature for the west. For long-term moisture, we replaced the Buildup Index with the nationally calibrated Z-index.

Preliminary tests indicated that, for most of the country, the live fuel damping model improved on simple climatology as a seasonal indicator of reduced fire activity. We also found about a 2-week buffer between the onset (or termination) of live fuel damping and large wildland fires. The model appears to be applicable in North American temperate and subtropical climate zones where the annual temperature cycle (not the annual moisture cycle) is the primary factor governing fuel phenology.

Résumé

Les gestionnaires locaux des feux de forêt se rendent facilement compte du verdissement des forêts et de la diminution des incendies qui en résulte. Ces phénomènes sont toutefois moins évidents à l'échelle régionale et nationale. De plus, on comprend mal l'impact de la sécheresse sur la phénologie du combustible vert. Enfin, les chercheurs analysant les bases de données météorologiques historiques ne disposent généralement pas de données phénologiques. Le présent article décrit un modèle météorologique qui suit l'impact du verdissement sur la gravité des feux de friches.

Nous avons obtenu 20 années de données météorologiques quotidiennes de 148 stations du National Weather Service situées dans chacun des cinquante États américains. Elles ont été appariées à 15 années de données informatisées sur les incendies provenant de 100 forêts nationales. Nous avons également utilisé 18 mois de données météorologiques provenant de 600 stations situées d'un bout à l'autre du pays conjointement avec des données sur 700 grands feux (500 acres et plus) s'étant produits dans 34 États.

Le modèle a commencé à être élaboré à partir d'un modèle inédit sur le stade herbacé de Keetch (1971). Ses tableaux de codes de stations, destinés à l'origine à l'Est des États-Unis, ont été élargis afin d'en augmenter l'applicabilité. Nous avons ajouté une composante "élévation" au calcul de code de station - une caractéristique essentielle pour l'Ouest. Pour l'humidité à long terme, nous avons remplacé l'indice "buildup" par l'indice Z étalonné à l'échelle nationale.

Des essais préliminaires ont révélés que, dans la majeure partie du pays, le modèle de la teneur en humidité du combustible vert s'est avéré meilleur que la simple climatologie comme indicateur saisonnier de la diminution de l'activité du feu. Nous avons également découvert l'existence d'une période tampon de 2 semaines entre l'abord (ou la diminution) de la teneur en humidité du combustible vert et l'apparition de grands feux de friches. Le modèle semble être applicable dans les zones tempérées et subtropicales de l'Amérique du Nord où le cycle annuel des températures (non pas le cycle annuel de l'humidité) est le principal facteur régissant la phénologie des combustibles.

Introduction

Although the concept of fire seasons is as old as fire-danger rating, it remains ill defined. In the Eastern U.S. for example, fire activity is high in the spring, relatively low in the summer, and moderate in the fall. A severe drought, however, can result in spring-like activity levels during the summer, thus confusing the issue. Fire management activity levels (and consequent expenditures) are closely related to the seasonal progression of fire activity. There is,

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

however, no consistent, reliable, objective method for determining the transition between one part of the fire season and another. As a result, fire management levels may not be well matched to fire activity levels during transition periods.

This paper describes a weather-based fire season model that combines a temperature-based green-up module applicable in 45 temperate-zone states and a winter module applicable to the entire United States. The model combines existing scientific knowledge, experienced judgement, and empirical evaluation. Output from this model can guide fire managers in delineating fire season transitions more accurately than existing methods and in damping fire severity during the off season. It also provides a basis for fire climate analyses of standard meteorological databases.

Review

Climate-based methods are often used to delineate transitions between one part of the fire season and another. Climatic transitions typically yield fixed dates that may be based on subjective experience or quantitative analyses of relative fire activity (e.g., Haines and Johnson 1975).

One problem with such methods is that, in a specific year, actual transitions could differ from the climatological mean by 2 to 4 weeks or more (Main 1987), resulting in unnecessary fire management expenses or inadequate preparedness. Another problem is that there is no generally accepted method for determining seasonal transitions. As a result, adjacent fire management agencies might be in different preparedness modes (some established by law) while they are experiencing similar fire activity.

Variable transitions, such as 3 days after snow melt or 3 days after the end of spring run off (Canadian Forestry Service 1970), solve some of the climatic problems but only for the winter/cured transition. More problematic, the onset of green-up relevant to fire behavior is critical (Burgan 1979, Bradshaw et al. 1983) and it is subject to interpretation, yet no guidelines are available for interpreting fuel phenology. In one case, specifying the onset of green-up just 4 days prior to the 24,000 acre Mack Lake fire (May 5, 1980) resulted in a fire-danger index that was one class lower than actually existed on the day of the fire[1].

Specifically, the threshold amount of green material (relative to the entire fuel complex) that is sufficient to significantly dampen fire behavior is not known. Present models factor all the live fuel moisture into the combustion process (Fosberg and Schroeder 1971, Albini 1976) yet field observations under marginal conditions disclose that green fuels are often only partly consumed or bypassed as the fire consumes the cured fuels. Possibly modeling green fuels as a radiation shield as well as a partial heat sink might prove more realistic. Further complicating the process, Deeming (1983) states that "the models do not work" when conditions do not follow typical seasonal patterns. Using the phenology of indicator species as an empirical model has been suggested, but the problem of determining appropriate species remains unresolved, as does the difficulty of finding broadly applicable species.

Still another problem of nonstandard methods is that the requisite data are generally not available in databases other than those archived by individual fire management agencies. Even when the data are available, as with the Automated Forest Fire Information Retrieval and Management System (AFFIRMS) (Furman and Brink 1975, Helfman et al. 1980), a survey of the database disclosed occasional inconsistent season transition dates. This suggests that green-up may have been used, in some cases, to adjust National Fire-Danger Rating indices, rather than to indicate true fuel phenology. This may have reflected field calibration of the system (such "tuning" is recommended by Burgan, 1979). In any case, such inconsistencies complicate large-scale fire climatology research.

Main (1987) described and extended the unpublished work of Keetch[2], who developed a temperature-based fire season threshold indicator for the Eastern United States. The process accumulates spring and fall degree days to determine season transition dates. It also incorporates latitude-based station codes to reflect more rapid seasonal transition with increasing latitude. The method was tested in Pennsylvania using the 10% of peak fire activity criteria developed by Haines and Johnson (1975). The method predicted seasonal transitions within 2 weeks of the observed crossing of the 10% relative fire occurrence threshold 44% of the time in the spring and 80% of the time in the fall. The primary difficulty related to extension of spring activity levels into the summer season as a result of drought.

Model Design

The fire season model described here is one component of a national wildland fire severity index. The index predicts the daily probability of a large (500+ acre) wildland fire within each of 390 climate divisions (CD) across the country. A set of design criteria were established for the season model. These were:

Applicability - The index was intended for year-round national use. Therefore, the seasonal component had to be as broadly applicable as possible.

Accuracy - As a large-scale index, it does not need the precision or accuracy of models intended for site-specific fire behavior prediction or local fire-danger rating.

Generality - As a component of a multi-agency system, the season model had to be based strictly on standard weather data available through the National Weather Service network.

Bias - The consequences of early and late season transition prediction errors are not equal. Therefore, the model should include a non-dampened buffer to compensate for imperfect information.

The severity index consists of six components: upper air, spread, short-, mid-, and long-term moisture, and season. The first five components are positive, indicating increasing severity with increasing component levels. The season component tracks the damping of wildland fire severity resulting from seasonal processes that are not well modeled by existing danger-rating systems. Season is, therefore, a negative component - indicating decreasing severity with increasing component levels. Each positive component has a range of 0 to 4 points, yielding a maximum possible internal index value of 20 points. This provides the numerical scale for season model damping.

The season model consists of two modules: green-up and winter. Green-up stratifies the season into five subseasons: pregreen cured, greening, green, curing, and postgreen cured. In addition to determining subseason transition dates, both modules calculate a season damping effect (component level).

Green-up

STATION CODES

The first step in the Keetch method involves calculating latitude-based spring and fall weather station codes. Essentially, as latitude increases, stations require smaller increments to trigger season transitions. Keetch used four equations to determine station codes (spring, fall, north of 38°, south of 38°). As a proven system, we chose to retain as much of Keetch's framework as possible. To extend Keetch's system to the Western U. S., we added an elevation adjustment to the latitude effect on temperature. We compared the standard dry adiabatic lapse rate of 10.2°C per 1,000 m of elevation[3] with spring and fall climatic temperature contours for the central U.S. (Environmental Data Service 1968). We found that 10.5° of latitude was roughly equivalent to 1,000 m of elevation. Using this relationship, we calculated an elevation coefficient with the same magnitude of effect on station codes as that for latitude.

We used the preceding as a starting point to calculate station codes for 606 hourly stations across the country that are part of the METAFIRE input network (Simard and Eenigenburg 1989). We then compared western season transition dates resulting from the station codes with 16 years (1970 to 1985) of observed fire activity data for 117 National Forests that have been archived in the National Fire Occurrence Data Library (Yancik and Roussopoulos 1982). We also compared them with length of growing season data (Environmental Data Service 1968). We then adjusted the station code elevation coefficients slightly to obtain a reasonable fit with both data sets. The preceding testing/adjustment process was repeated twice; final equations for calculating station codes are:

spring, ≥38°N $SC = 33.7 - 0.55\ LAT - 0.0045\ (ELEV - 300)$ (1)

<38°N $SC = 54.6 - 1.10\ LAT - 0.0045\ (ELEV - 300)$ (2)

fall, ≥38°N $FC = -0.36 + 0.32\ LAT + 0.0035\ (ELEV - 300)$ (3)

<38°N $FC = -17.08 + 0.76\ LAT + 0.0035\ (ELEV - 300)$ (4)

where: SC,FC = spring and fall station codes, respectively,
LAT = latitude (°), and
ELEV = elevation (meters).

Subtracting 300 meters from the station elevation incorporates the range of elevations of the 24 stations used by Keetch in developing his original thermal increment tables.

Equations 2 and 4 extend the southern range of Keetch's station codes (see Main 1987) to include Florida and Hawaii (20°N). Adding high-elevation stations required a similar extrapolation at the other end. Thus, there are 30 spring and 22 fall station codes in our model (compared to 20 and 15, respectively in Keetch's method). These extensions result in different constants than those listed by Main (1987); latitude coefficients remain unchanged. At 2,170 meters (the maximum station elevation in our database) the northern limit of Equations 1 and 3 is 45°N; at sea level, the northern limit is 60°N.

Keetch found that adjusting the spring station code by 1 point changed transition dates by 3 to 5 days (the lower resolution limit of his observational data). A 2-point adjustment changed the date by 7 to 10 days. Thus, the 20° to 60° range of latitude yields a 3-month range for spring transition dates. Based on the relative magnitude of the fall latitude coefficients, the range of fall transition dates should be approximately 2 months. The maximum elevation of 2,170 m yields a 1-month range of transition dates.

SEASON TRANSITION DATES

The model accumulates thermal increments similar to growing-degree days used in agriculture or heating degree-days used for determing fuel consumption. A similar method was developed by Thompson and Moncrieff (1982) for predicting the onset of bud break in Douglas fir. Keetch's method begins accumulating temperatures on March 1, which is appropriate for the Eastern U. S. For a national system, it is necessary to begin on January 1 (or the first day that the burning-day code changes from winter to spring - see the winter module, discussed subsequently). After initiating the spring and fall transition periods, Keetch's method continued tabulating thermal increments to determine the end of the periods.

Adaptation to western conditions as well as the method used to calculate the magnitude of the damping effect (discussed subsequently) necessitated a predetermined duration approach. In one study, first bud break through first visible leaf for multiple species on four sites on the Cumberland Plateau in Tennessee spanned 40 days (McGee 1986); this does not include grass nor total leaf development, which extend the transition period at both ends. For fire behavior purposes, however, the primary interest is in the threshold portion of the greening period rather than the entire period. There is little effect in the early stages of greening, and an overwhelming effect in the latter stages. Thus, Keetch's tables yield relatively short (10 to 20 day) average durations for the greening period. This compares well with the National Fire-Danger Rating System (NFDRS) with a range of 1 to 4 weeks, based on moisture-dependant climate classes (Cohen and Deeming 1985). We, therefore, judged that a duration range of 15 to 30 days for greening was appropriate for the intended use of the season model. This is achieved with:

$$DT_g = 15.0 + 0.5\ SC \qquad (5)$$

where: DT_g = greening duration (days).

Both Keetch and the NFDRS use an abrupt transition from green to cured. Field observations indicate, however, that in northern climates, some vegetation does not cure even after a "killing frost" (e.g., -5°C) and that some time is required to dry out after the vegetation dies. We, therefore incorporated a "curing" duration range of 12 to 25 days to provide a smooth transition between green and cured. This is achieved with:

$$DT_c = 25.0 - 0.6\ FC \qquad (6)$$

where: DT_c = curing duration (days).

In the Eastern U.S., termination of the green period is based on Keetch's fall temperature increments. An approximate precalculated duration is needed, however, for calculating the green-up damping effect. After examining average fall transition dates obtained from the Keetch method, we derived a simple relationship that reasonably matched his results:

$$DG_e = 50 + 4.0\ SC \qquad (7)$$

where: DG_e = duration of the eastern green period (days).

Equation 7 yields a range of 78 to 154 days (station code range = 7 to 26) for the precalculated (not actual) green period duration in the Eastern U.S. (roughly east of 99° longitude). Note that the duration of greening and curing must be added to the green duration to determine the total period when a damping effect is applied.

Although fall temperature increments work well in the East, they are inappropriate for terminating western green-up, where normally dry summers play a dominant role. The model, therefore, calculates green-up duration for western stations based on fuel type and spring station code:

brush $DG_b = 45 + 1.0\ SC$ (8)

conifer $DG_c = 40 + 0.8\ SC$ (9)

grass $DG_g = 32 + 0.7\ SC$ (10)

The duration of the green period for grass ranges from 32 to 53 days. This range was designed to bracket the 45-day duration used by Burgan (1979) for the NFDRS annual grass herbaceous fuel moisture. The duration for conifers ranges from 40 to 64 days; that for brush is 45 to 75 days. The latter two were adjusted so that western green-up was completed just prior to observed large early summer wildfires. Note that the total green-up period duration is the sum of $DT_g + DG + DT_c$.

The model is not applicable in nontemperate-zone regions or where green-up is not temperature driven. Therefore, five states are currently excluded: Florida and Hawaii (tropical), Arizona and New Mexico (desert), and Alaska (arctic). Variants of the green-up model for these states may be developed in the future.

GREEN-UP EFFECT

The last part of the model involves calculating the green-up damping effect on the severity index. Calculating the green-up effect independently from season transition dates (rather than switching back to spring) solves the major problem with the Keetch system encountered by Main (1987). That is, switching back to a spring stage during the summer (a) overestimated actual severity by reducing the effect to 0 and (b) resulted in internal inconsistencies in model logic. Previous studies have shown that existing live-fuel moisture models did not perform satisfactorily in some climates and seasons (Loomis et al. 1979, Loomis and Blank 1981). The present model uses only their general sense of the seasonal progression of live fuel moisture.

The maximum green-up effect has been intuitively set for eastern hardwoods so that the severity index (obtained from the other five components) must be above the warning threshold to result in an advisory. For example, an advisory requires 7 points, a watch 11 points, and a warning 15 points on a 20-point internal severity index scale. The maximum green-up effect for hardwoods is 9 points, meaning that the index would have to be at least 16 points before incorporating green-up damping to exceed the advisory threshold. This almost (but not completely) precludes an advisory. The maximum value for brush is 8, for conifers it is 7, and for grass it is 6.

Although existing green-up models assume a linear transition, we feel that neither the rate of greening nor the transitional effect of greening on fire activity are linear. Greening would seem to be a normally distributed process with an s-shaped cumulative distribution. Initially, a few hardy species break dormancy; the bulk of the species green up during the middle of the transition; finally, a few species, at the northern limit of their range gradually complete the process. Initially, greening would have little effect on fire behavior but as the percent of green material crosses an as yet undefined threshold, the effect rises rapidly to effectively overwhelm fire activity. Since our greening transition excludes both tails of the process, we subjectively chose an exponent of 1.5 to model the green-up effect during the middle of the transition. We felt that a stronger exponent resulted in too abrupt a change, thereby necessitating more than attainable accuracy in determining the starting date.

The equation for green-up effect during the greening transition is:

$$GE_1 = M_f\ (\text{days} / DT_g)^{1.5} + DE \tag{11}$$

where: $GE1$ = green-up effect (greening transition)
GM_f = maximum value of the green-up effect for fuel f
days = no. of days since the start of the current period
DE = drought effect (explained subsequently)

Equation 11 raises GE from 0 to 100% of the maximum value, based on the proportion of the total duration completed as of the date of calculation. The drought effect (DE) will be discussed subsequently.

Numerous authors have measured and/or modeled live fuel moisture: Burgan (1979), Countryman (1974), Blackmarr and Flanner (1968), Howard (1978), Jameson (1967), Loomis et al. (1979), Olsen (1960), Philpot (1963), Reifsnyder (1961), Wendel and Storey (1962), and Van Wagner (1967). The form of the seasonal live moisture trend is as varied as there are plant species, different parts of each plant, or climate. The trends vary from gradual rises and dips for wood and old foliage, through approximately linear decreases when noisy data preclude more accurate modeling, to moderate exponential drying for brushy species, and finally, steeply exponential drying for new foliage and grass. We subjectively chose the exponent 2/3 to represent the moderate drying category (roughly corresponding to the typical NFDRS 1,000-hr timelag fuel moisture model shown by Burgan 1979).

The equation for green-up effect during the green period is:

$$GE_2 = GM_f\ (1.0 - GM_p\ (\text{days} / DG_f)^{2/3}) + DE \tag{12}$$

where: GE_2 = green-up effect (green)
GM_p = percent of GM on last day of the green period (0.35 for eastern conifer or grass, 0.5 otherwise)
DG_f = duration of green period for fuel f

Equation 12 reduces GE from the maximum value to a predetermined residual, based on the proportion of the total duration completed as of the calculation date.

The equation for green-up effect during the curing transition is:

$$GE_3 = GE_e\ (\text{days} / DTc) + DE \tag{13}$$

where: GE_3 = green-up effect (curing)
GE_e = GE value on the last day of the green period

Equation 13 reduces the green-up effect from its value on the last day of the green period to 0. Since, in the season model, the primary purpose of curing is to provide a smooth transition from green to cured, a simple linear function was considered adequate for the task.

The seasonal progression of the green-up effect is shown in Fig. 1. It is plotted in relative terms (e.g., prior to multiplication by GM_f or GE_e) to show the generic form of the function. The curves in Fig. 1 are illustrative - not mathematically derived.

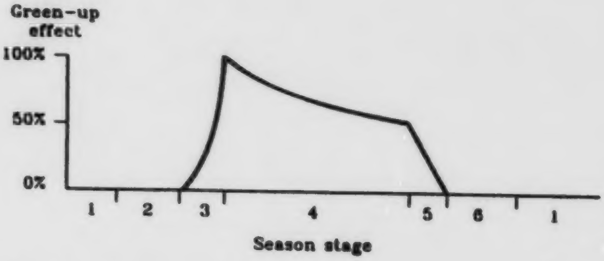


FIG. 1. A stylized seasonal progression of the green-up effect shown as a percentage of the maximum effect. Seasonal stages are: winter (1), cured, spring (2), greening (3), green (4), curing, summer/fall (5), and cured, summer/fall (6).

Drought can significantly affect green-up damping. In previous research, Simard et al. (1987) found that the monthly moisture anomaly (Z-index) of the Palmer Drought Index (Palmer 1965, Karl 1985) outperformed other long-term moisture balance models in predicting the probability of large fires. Based on availability within the METAFIRE system, the Z-index was a natural choice for incorporation into the green-up model (Canadian FWI Buildup Index for Alaska and Hawaii). The Z-index is first reversed and converted to a long-term component (LT) on an approximately 100-point scale:

$$LT = 10\ (5 - Z) \tag{14}$$

Several authors have related live fuel moisture to soil moisture or long-term moisture balance models. Results range from no relationship (Reifsnyder 1961) through "apparently correlated" (Olsen 1960, Philpot 1963) to linearly related (Burgan 1976, Jameson 1967). Given the present state of knowledge, we chose a simple linear relationship. Burgan found relationships with six species in which the drought effect spanned an average 62% of the observed moisture range. We derived equations such that the drought effect under extreme conditions would be two-thirds of the average GM value for all four fuel classes.

The effect of drought on green-up (DE) is computed with:

$$LT \le 30 \qquad DE = 2.0 - (LT / 30) \tag{15}$$

$$30 < LT < 65 \qquad DE = 0.0 \tag{16}$$

$$LT \ge 65 \qquad DE = ((65 - LT) / 8.2) - 1.0 \tag{17}$$

If conditions are unusually wet (Eq. 15), the green-up effect is enhanced by 2 points at LT = 0 (27% of the average GM value). This offsets up to half of the normal built-in curing during the green stage. During a range of normal conditions (Eq. 16), we assume that there is no measurable effect of small variations in rainfall. During drought (Eq. 17), the green-up effect is reduced by 5 points at LT = 100. Drought can effectively shorten the green-up period (although transition dates remain unchanged) by reducing the green-up effect to zero.

Winter

Traditionally, fire-danger indices are not calculated during off-seasons. Our database includes fires during every month, however, meaning that on a national scale, there is no off-season. It is more appropriate to think in terms of more and less active seasons. A national system that operates 365 days per year poses some unique problems not encountered by a dispatcher who can observe conditions outside the window.

SNOW

The snow module subtracts 9 points (SE = 9) from the severity index (maximum value = 20) when snow is reported on the ground. The value 9 was selected to reduce most indices to 0 and virtually preclude any day from being above the advisory threshold when snow was reported on the ground. Although a larger value might have been chosen to insure the desired effect, we retained a single digit for logistical compatibility with other components of the severity index. The snow effect is reduced by 1 point per day after the last day that snow is reported to reflect the lag between snow melt and the ground drying sufficiently to carry large fires. This 9-day lag is based on examining weather data for a limited number of major early season fires conducted as part of developing a prototype extreme fire potential index[4]. Although this feature is often redundant because indices are typically low during winter, an occasional warm, dry, windy day can result in high indices despite the presence of snow on the ground.

TEMPERATURE

A second winter adjustment involves reducing the severity index when the minimum daily temperature falls below 30°F. The reasoning is that (a) major fires do not occur when temperatures are below freezing or (b) when frozen ground thaws, the fuels in contact with it are too wet to support large fires. The temperature effect (TE) is calculated with:

$$TE = (31 - T_{min}) / 2; \quad TE \le 6 \qquad (18)$$

where: T_{min} = minimum 24-hour temperature (°F).

Unlike snow on the ground, low temperatures, by themselves, do not preclude large fires. Rather, they significantly reduce the probability of occurrence. For that reason, we limited the temperature effect to 6 points. Again, this is adequate on most days, because associated severity index components will normally be low. Note that there is no cumulative process in the temperature module - it simply reflects conditions on a single day.

BURNING DAYS

We have successfully used a burning-day concept in climatological studies in which, for example, data on the presence of snow on the ground were unavailable. In spring, 3 consecutive days with maximum temperatures of 45°F or greater are needed to begin the fire season. If any day in the sequence falls below 45°, the counter is reset to 0. A similar threshold (48°F) was found to be a good predictor of snow melt in Southern Canada (Simard and Valenzuela 1972). Although Main (1987) also required that there be no rain exceeding 0.1" during the 3-day period, we felt that was unnecessary because rain would inherently reduce the severity index components. All days within the fire season are classed as burning days.

During the late fall, an inverse process is used to determine the winter transition -- 3 consecutive days with maximum temperatures of 45°F or less. All days after the cool spell are classed as non-burning days. Following the same reasoning as for minimum temperature, the module reduces the severity index by 6 points on non-burning days (BE = 6), requiring at least a mid-level watch to yield a final advisory. At the beginning and end of winter, and throughout the winter in the South, the module can oscillate between burning and non-burning days, as each of the transition criteria is met. The key feature of the procedure is the 3-day lag required to switch from one season to the other. This module reduces the number of isolated advisories resulting from individual warm, dry, windy days during an otherwise cool, wet winter.

The 3-day rule is modified slightly in the spring. If $T_{max} \ge 65°F$ on any single day, BE = 4. If, in any 2-day sequence, $T_{max} \ge 50°F$ on day 1 and $T_{max} \ge 55°F$ on day 2, BE = 0 (the second rule overrides the first). The purpose of these modifications is to reduce BE more rapidly during an unusually rapid change from winter to spring conditions. These spring heuristics are based on examining weather data for large early season fires contained in our large fire database.

The Composite Model

The green-up and winter modules become significant at different times of the year. Thus, in virtually all cases, if GE > 0, then SE, TE, and BE = 0, and vice-versa. In any case, the severity index is reduced by the maximum value of GE, SE, TE, or BE. For processing simplicity, the present model treats the winter modules as absolute limits (obvious for snow covers most fuel, perhaps debatable for temperature and burning days). Therefore, the winter effects are allowed to reduce the severity index to 0. Because burnable fuels are present during green-up, the maximum reduction allowed is two-thirds the value of the severity index. This significantly reduces the number of days above the threshold during green-up but precludes index values of 0 during otherwise moderate fire weather conditions. In effect, although green-up can dominate fire activity, it is not the only process influencing start and spread.

Model Evaluation

We evaluated the season model within the context of the METAFIRE system (Simard and Eenigenburg 1989). Two databases were used to develop and evaluate the overall system; a third was used for the season model. The first consists of 576 days of weather data for each of 390 climate divisions across the U. S. From another perspective, the weather database contains 224,640 climate-division (CD) days acquired over a 22-month period. The value of the severity index was calculated for every CD-day (except for 0.5% missing data).

We calculated the value of each seasonal component for varying subsets of this database. This variability reflects the gradual evolution of model development and acquisition of additional types of weather data as the test period progressed. For example, the green-up module test began in the summer of 1987. The current version of the temperature and burning-day modules can be evaluated starting in mid-July, 1989 (in conjunction with acquiring maximum and minimum temperature data). An earlier (less effective) version of these modules (based on 1 pm temperature data) can be tested from June, 1987. Finally, snow data were first acquired in mid-January, 1989. Although evaluation of the winter modules is somewhat limited, there are enough data to develop preliminary performance statistics.

The second database consists of 1,262 CD-days when one or more wildland fires made a run of 500 acres or more. From another perspective, we acquired data on 998 fires that made 1,821 large runs during the 22-month test period. The fires occurred in 177 CDs (45.4% of the total number) in 38 states -- a representative national sample.

Finally, we used a National Fire Occurrence Data Library (NFODL) database to develop criteria for evaluating model performance. The NFODL system archives data for all fires reported on National Forest land. There are 117 National Forests with a continuous 16-year record from 1970 to 1985. For these forests, we assigned weights to every fire based on size class: A = 1, B = 2, C = 4, etc., through F+ = 32. Doubling the weight per size class incorporates an increased fire load for larger fires. We then calculated average fire activity (sum of the weights for all fires / 16) for every week of the year. Since our interest is in large fires only, we used a modified version of a fire season criterion developed by Haines and Johnson (1975). We classed all weeks having 20% or more of the peak 1-week activity as within the fire season and all other weeks as out of season (rather than their 10% criterion).

This analysis disclosed a range of fire seasons for individual forests lasting from 10 weeks (Allegheny) to 52 weeks (Florida). Regional averages ranged from 17.7 weeks (Intermountain) to 32.4 weeks (Southern). The national average for all 117 Forests is 21.7 weeks, with a standard deviation of 4.7 weeks. Thus, our model should reflect in-season conditions 21.7 / 52 or 42% of the time.

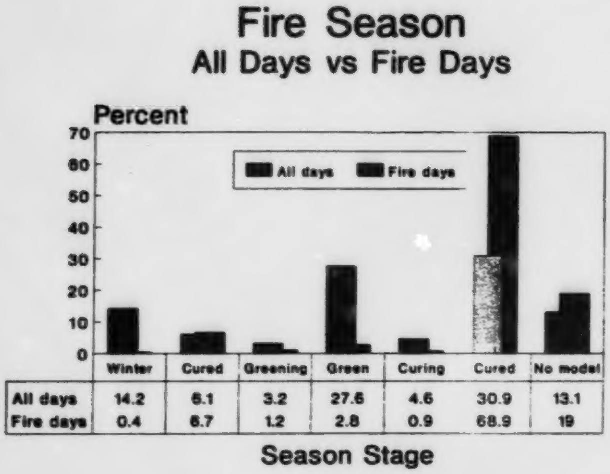
Timing of the seasonal transitions is equally important. We used two measures to evaluate transition date accuracy. First, for all fires within 30 days of the seasonal transition, there should be an average 1-week lag between the transition date and the first (or last, as appropriate) large fire. Extending beyond 30 days, in our opinion, simply biases the sample and no longer reflects transition accuracy. The second measure is that at least 80% of all large fires in the 30-day test window should be on the fire-season side of the transition.

The NFODL database also yields a measure of the percentage of all fires that should occur outside the fire season, as we have defined it. Taking a sample of two forests at opposite ends of each region (n = 18), we calculated an average 10.2% (se = 5.1%) of all fire activity during the off season. Because large fires should be less frequent than all fires during the off season, this value provides an upper limit for what our model should reflect. Finally, the fact that some large fires occur during what we class as the off season does not necessarily indicate model error. The severity index could be high enough to override the damping effect, or drought could reduce the effect. Thus another criteria is that not more than 2% of all days with off-season fires should be reduced from above to below the advisory threshold.

Results

In 1988, the duration of the combined greening, green, and curing periods for the Eastern U. S. ranged from 138 days (northern Maine) to 270 days (south Texas). For the Western U. S., the duration ranged from 106 days (southern California) to 62 days (Colorado mountains). The duration of green conditions cannot be directly compared with frost-free periods or average growing seasons because the processes differ somewhat.

Overall, the season model classed nearly 50% of all CD-days in our archived database as out of season (winter or the three green stages), 37% as in season (cured), and for 13% of all days, the model did not apply (Fig. 2). For evaluation purposes, we prorated the no-model data into out of season (57%) and in season (43%). The latter is surprisingly close to the 42% in-season target calculated from the NFODL data. The out-of-season breakdown by module is: green-up -



	Winter	Cured	Greening	Green	Curing	Cured	No model
All days	14.2	6.1	3.2	27.6	4.6	30.9	13.1
Fire days	0.4	6.7	1.2	2.8	0.9	68.9	19

FIG. 2. Comparison of all CD-days (n = 257,500) and large-fire CD-days (n = 1,276) vs season stage in percent.

35.4%, temperature - 24.0%, burning days - 14.2%, and snow - 3.2%. Note that for this evaluation, a classification of winter is based on the burning day module only. This underestimates the actual percentage of days with winter conditions. We expect to determine the joint probability of all three winter modules as additional data are acquired. The results for snow on ground reflect a limited test period; the percentage of days will increase as data acquisition continues.

In testing model transitions, we found that the eastern spring season ended an average of 3.7 days after the last reported large fire. The eastern fall season began an average of 7.9 days before the first large fire. In the West, the summer season began an average of 9.8 days before the first large fire. Although somewhat close for the eastern spring, the overall average buffer of 7.1 days matches the design criteria well. A minor change in the method of calculating spring station codes should increase the eastern spring buffer by 2 to 3 days.

There were 93 large fires reported during the 30-day green-up transition test window. Of these, 71 (76%) were on the fire season side of the transition, 4 were on the exact date (4%), and 18 (19%) were on the off-season side. This just meets the criteria for fire season transition date accuracy. Seven of the 18 misses were within 3 days of the transition and can be captured with minor adjustments to the transition processing routines.

The limited sample precluded testing transition dates for the winter modules. Of 17 fires that occurred on days classed as winter, 14 were associated with an earlier version of the temperature and burning day algorithms. Although the improved versions cannot be tested against the existing data, we expect performance to improve as more data are acquired. Further, some of these fires can be captured with minor adjustments to the winter module thresholds.

From an overall perspective, 66 large fires (5.3%) occurred during the off season as classified by the model -- half of the 10% upper limit calculated from the NFODL data (Fig. 2). Of this total, 49 fires (3.9%) occurred during green-up and 17 fires (1.4%) occurred during winter or when minimum temperatures were below the threshold. Fourteen of the off-season fires (1.1%) had a damping effect of 0; 19 (1.5%) remained above the advisory threshold after the damping effect was applied; and 17 (1.4%) were below the threshold before damping was applied. Thus, only 16 fires (1.3%) were lost as a result of seasonal damping -- less than our 2% criteria.

We evaluated the model in its role as a component of the fire severity index - the primary purpose for which it was designed. To do this, we compared the season model's performance as a large-fire discriminator with that of the other five index components. One simple measure of the discriminating power of an index is the difference between the percent of days above a threshold and the percent of fires that occur on those days. For the season model, 50.1% of all days were classed as in season (including all no-model days - Fig. 2). Conversely, 94.7% of all fires occurred on such days. The difference between these two is 44.6 - the second highest value for all six index components. By comparison, the mid-term component is the best individual discriminator (difference = 56), and the spread component is the poorest (difference = 19). Thus, the season model is an important addition to the severity index.

From another perspective, the effectiveness of the season model can also be measured by contrasting the number of days when the severity index was reduced vs. the number of large fires that occurred on such days. Seasonal damping was greater than 0 on 123,327 CD-days (54.9%). Fifty-two fires occurred on such days. Dividing the former by the latter yields 2,372 days of damping per fire day. Clearly, the season model is a very effective filter.

The annual progression of the season model on a national scale can be seen in Figures 3 through 6. Recall that the tested version of the green-up module is not applicable in Florida, Arizona, New Mexico, Alaska, and Hawaii. Also, data for Figs 3-6 were obtained through an operational data acquisition system with a missing data rate of 0.5%.

By April 1, 1988 (Fig. 3), the Southeast was greening and much of the Northeast was in the spring fire season, except for the northernmost portions that still reflected winter conditions. In the West, the coastal areas were already fully green, the lower station elevations of the interior were in transition, and the higher elevations were in a cured state. Parts of Wyoming and all of Alaska were still in winter.

By May 1, 1988 (Fig. 4), all the Southeast and most of the West were green. Most of the Northeast and a few high-elevation western CDs were greening. The northernmost portions of the Northeast were still in the spring fire season and most of Alaska remained in winter.

By mid-June most of the West had cured and all of the East was green. The pattern remained essentially unchanged through the summer. By October 1, 1988 (Fig. 5), most of the East remained green, but the northern tier of states had started curing, and a few CDs were already into the fall fire season. Parts of Alaska showed winter conditions.

One month later, on November 1, 1988 (Fig. 6), most of the country indicated cured conditions. Parts of the Southeast were in transition, and southern Texas remained green. Winter had begun in most of Alaska and a few northern CDs.

The overall progression of seasons generated by the model follows a reasonable pattern, thus providing visual confirmation of what the numerical analysis indicated.

Conclusion

We consider the season model described here as primitive. Given the present state of the art, there are few mechanistic or process-driven relationships. Although based, where possible, on scientifically derived knowledge, the model relies heavily on empirical observations and heuristic rules. This results from the need to derive, in a relatively short time, a broadly applicable model of a particularly complex process. We demonstrated that the model works very well (the second best large-fire discriminator) in support of the severity index - the primary purpose for which it was designed.

An important stand-alone contribution of this effort is the development of a comprehensive framework for quantifying the effect of the annual fire season cycle on wildland fire severity. The model also provides objective weather-based guidance in delineating fire season transitions - a long-standing fire management problem. Of primary importance to fire managers, as a currently operational model rather than a theoretical construct, it can be implemented today. In five tests, the model averaged 93% successful in discriminating between in- and out-of-season conditions -- a very effective filter.

The model is broadly applicable in moist, temperate climates. We caution, however, that although the model has been broadly tested in a spatial sense, it has not been similarly tested temporally. Lacking the model, we can not measure climatological database for the model, over the long run. Further, the model has not been evaluated in detail on local scales. There are, no doubt, local climatic and phenologic situations (other than those already identified) where the model will not perform as well as described here. We, therefore, strongly advise local evaluation prior to implementing the model.

Although the model can be used in isolation, it is probably more useful in support of existing fire-danger rating systems. With additional development, refinement, and application, the season model described in this paper has the potential to significantly increase the precision with which fire season is incorporated into wildland fire management.

Endnotes

[1] Data on file at the USDA Forest Service, North Central Forest Experiment Station, East Lansing, MI. Although visible signs of green-up were evident on the day of the fire, the live fuels had little or no apparent damping effect on fire behavior.

[2] Memorandum on file at the USDA Forest Service, North Central Forest Experiment Station, East Lansing, MI.

[3] Our highest station elevation was 2,170 m. The dry adiabatic lapse rate predominates in the lowest portion of the atmosphere.

[4] Data on file at the USDA Forest Service, North Central Forest Experiment Station, East Lansing, MI.

References

ALBINI, F. A. 1976. Estimating wildfire behavior and effects. USDA For. Serv. Gen. Tech. Rep. INT-30, Intermountain For. Range Exp. Sta. Ogden, UT. 92 pp.

BLACKMARR, W. H. AND W. B. FLANNER. 1968. Seasonal and diurnal variation in moisture content of six species of Pocosin shrubs. USDA For. Serv. Res. Pap. SE-33, Southeastern For. Exp. Sta. Asheville, NC, 11 pp.

BRADSHAW, L. S., J. E. DEEMING, R. E. BURGAN, R. E., AND J. D. COHEN. 1983. The 1978 National Fire-Danger Rating System: technical documentation. USDA For. Serv. Gen. Tech. Rep. INT-169, Intermountain For. Range Exp. Sta., Ogden, UT. 44 pp.

BURGAN, R. E. 1976. Correlation of plant moisture in Hawaii with the Keetch-Byram drought index. USDA For. Serv. Res. Note PSW-307, Pacific Southwest For. Range Exp. Sta., Berkeley, CA. 6 pp.

BURGAN, R. E. 1979. Estimating live fuel moisture for the 1978 National Fire-Danger Rating System. USDA For. Serv. Res. Pap. INT-226, Intermountain For. Range Exp. Sta., Ogden, UT. 17 pp.

CANADIAN FORESTRY SERVICE. 1970. Canadian Forest Fire Weather Index. Dept. Fish. For. Ottawa, Ont. 25 pp.

COHEN, J. D. AND J. E. DEEMING. 1985. The National Fire-Danger Rating System: basic equations. USDA For. Serv. Gen. Tech. Rep. PSW-82, Pacific Southwest For. Range Exp. Sta., Berkeley, CA. 16 pp.

COUNTRYMAN, C. M. 1974. Moisture in living fuels affects fire behavior. Fire Manage. 35(2):10-13.

DEEMING, J. E. 1983. Reflections on the development, application and future of the National Fire-Danger Rating System. pp. 41-44. App. E. In: (L. S. BRADSHAW, et al. compilers). The 1978 National Fire-Danger Rating System: technical documentation. USDA For Serv. Gen. Tech. Rep. INT-169, Intermountain For. Range Exp. Sta., Ogden, UT.

ENVIRONMENTAL DATA SERVICE. 1968. Climatic atlas of the United States. USDC Environ. Sci. Serv. Admin., Environ. Data Serv. Washington, DC. 80 pp.

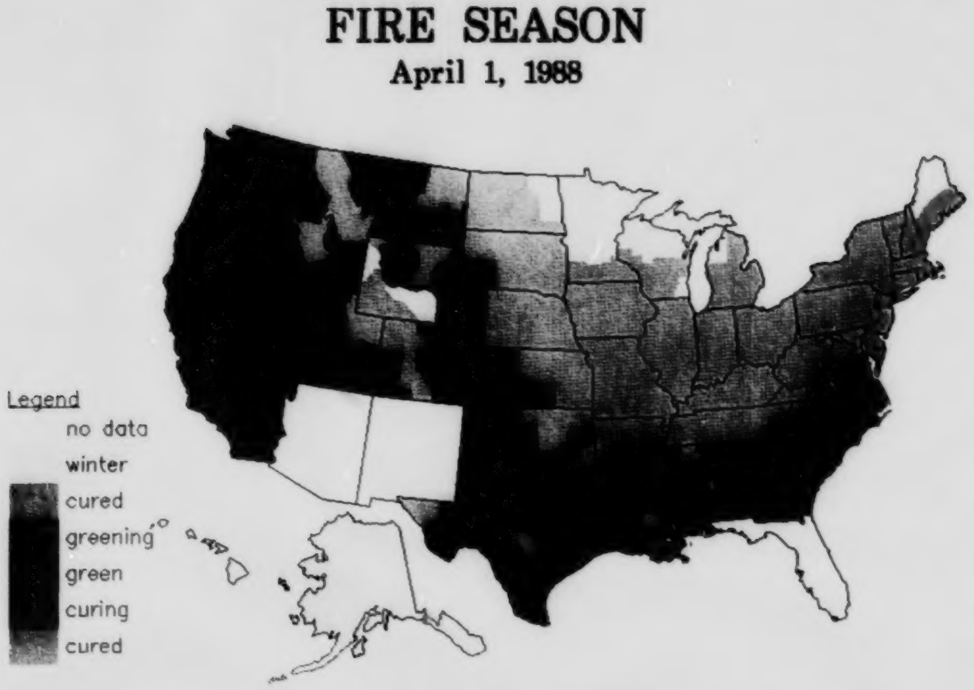

FIRE SEASON
April 1, 1988
Legend
no data
winter
cured
greening
green
curing
cured

FIG. 3. Season stage for April 1, 1988.

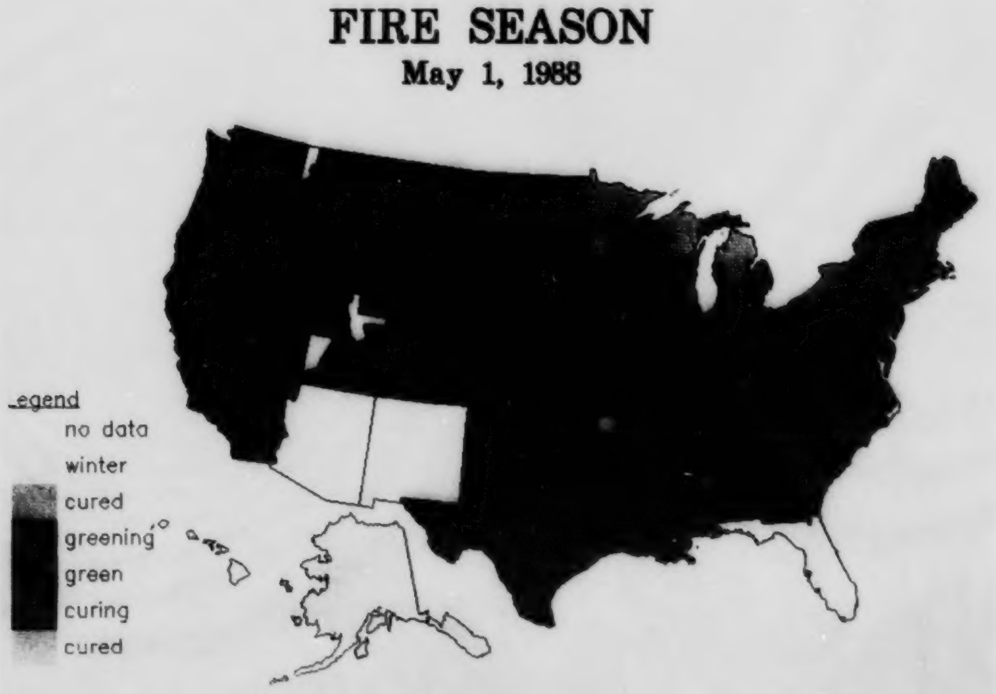
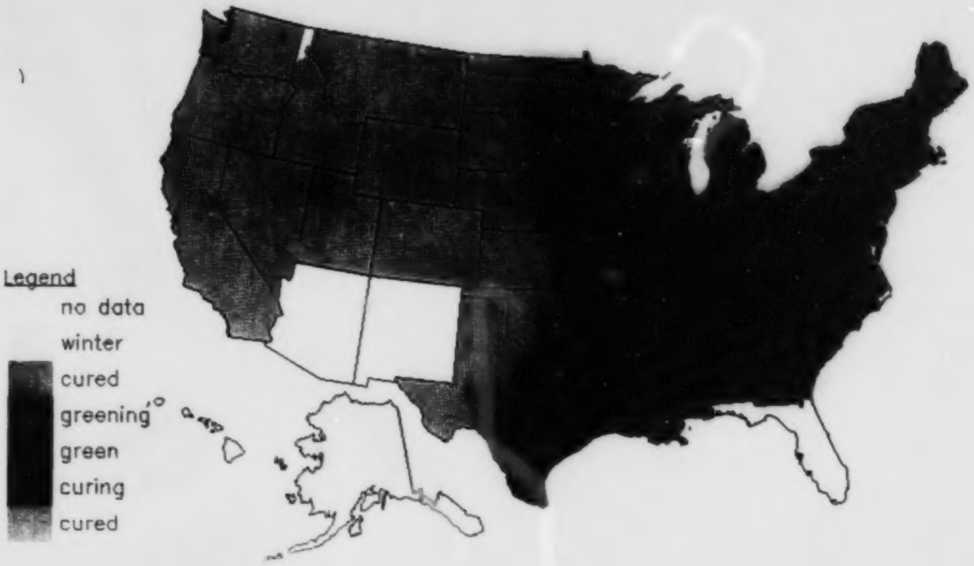

FIRE SEASON
May 1, 1988
Legend
no data
winter
cured
greening
green
curing
cured

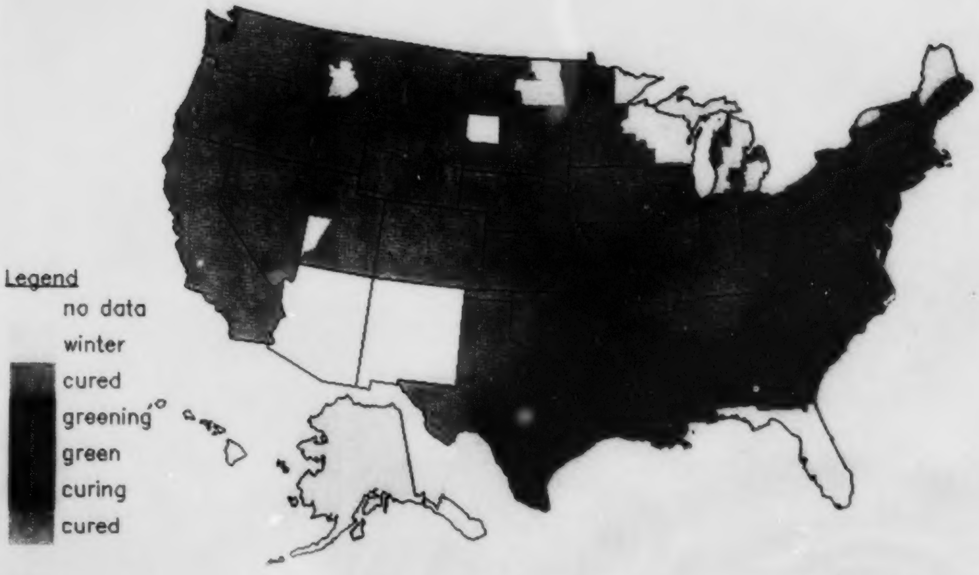
FIG. 4. Season stage for May 1, 1988.



FIRE SEASON
October 1, 1988

Legend
no data
winter
cured
greening
green
curing
cured

FIG. 5. Season stage for October 1, 1988.



FIRE SEASON
November 1, 1988

Legend
no data
winter
cured
greening
green
curing
cured

FIG. 6. Season stage for November 1, 1988.

References

FOSBERG, M. A. AND M. J. SCHROEDER. 1971. Fine herbaceous fuels in fire-danger rating. USDA Res. Note RM-185, Rocky Mtn. For. Range Exp. Sta. Ft. Collins, CO. 7 p.

FURMAN, R. W. AND G. E. BRINK. 1975. The national fire weather data library: what it is and how to use it. USDA For. Serv. Gen. Tech. Rpt. RM-19, Rocky Mountain For. Range Exp. Sta., Ft. Collins, CO. 8 pp.

HAINES, D. A. AND V. J. JOHNSON. 1975. When are fires in season? Fire Manage. 36(4):16-18.

HELFMAN, R. S., R. J. STRAUB, AND J. E. DEEMING. 1980. Users guide to AFFIRMS: time-sharing computerized processing for fire danger rating. USDA For. Serv. Gen. Tech. Rep. INT-82, Intermountain For. Range Exp. Sta. Ogden, UT. 150 pp.

HOWARD, E. A. 1978. A simple model for estimating the moisture content of living vegetation as potential wildfire fuel. pp. 20-23. In: Proc. Fifth Conf. on Fire and For. Meteorology, Atlantic City, NJ, March 14-16, 1978. Amer. Met. Soc., Boston, MA.

JAMESON, D. A. 1967. Diurnal and seasonal fluctuations in moisture content of Pinyon and Juniper. USDA For. Serv. Res. Note RM-67, Rocky Mountain For. Range. Exp. Sta. Ft. Collins, CO. 7 pp.

KARL, T. R. 1985. The sensitivity of the Palmer Drought Severity Index and Palmer's Z-index to their calibration coefficients including potential evapotranspiration. pp. 96-103. In: Proc. Eighth Conf. Fire For. Meteor., Detroit, MI. April 29 - May 2, 1985, Soc. Amer. For. Bethesda, MD, SAF. Publ. 84-04.

LOOMIS, R. M. and R. W. BLANK. 1981. Summer moisture content of some norhern lower Michigan understory plants. USDA For. Serv. Res. Note NC-263, North Central For. Exp. Sta., St. Paul, MN. 4 pp.

LOOMIS, R. M., P. J. ROUSSOPOULOS, AND R. W. BLANK. 1979. Summer moisture contents of understory vegetation in northeastern Minnesota. USDA For. Serv. Res. Pap. NC-179, North Central For. Exp. Sta., St, Paul, MN. 7 pp.

MAIN, W. A. 1987. Weather-based methods for delineating different northeastern fire stations. pp. 207-210. In: Proc. Ninth Conf. Fire For. Meteor., San Diego, CA. April 21-24, 1987. Amer. Meteor. Soc., Boston, MA.

MCGEE, C. E. 1986. Budbreak for twenty-three upland hardwoods compared under forest canopies and in recent clearcuts. For. Sci. 32(4):924-935.

OLSEN, J. M. 1960. 1959 green fuel moisture and soil moisture trends in Southern California. USDA For. Serv. Res. Note 161, Pacific Southwest For. Range Exp. Sta., Berkeley, CA. 8 pp.

PALMER, W. C. 1965. Meteorological drought. USDC Weather Bur. Res. Pap. 45. Office of Climat., Washington, DC. 58 pp.

PHILPOT, C. W. 1963. The moisture content of Ponderosa Pine and Whiteleaf Manzanita foliage in the central Sierra Nevada. USDA For. Serv. Res. Note PSW-39, Pacific Southwest For. Range Exp. Sta., Berkeley, CA. 7 pp.

REIFSNYDER, W. E. 1961. Seasonal variation in the moisture content of the green leaves of Mountain Laurel. For. Sci. 7(1):16-23.

SIMARD, A. J. AND J. E. EENIGENBURG. 1989. METAFIRE - a national information system for wildland fire severity. USDA For. Serv., North Central For. Exp. Sta., St. Paul, MN. Unpublished progress report, Jan. 1989, 61 pp.

SIMARD, A. J., J. E. EENIGENBURG, AND S. L. HOBRLA. 1987. Predicting extreme fire potential. pp.148-157. In: Proc. Ninth Conf. Fire and For. Meteor., San Diego, CA. April 21-24, 1987. Amer. Meteor. Soc., Boston, MA.

SIMARD, A. J. AND J. M. VALENZUELA. 1972. A climatological summary of the Canadian Forest Fire Weather Index. Environ. Canada, For. Serv., Inf Rep. FF-X-34, For. Fire Res. Inst., Ottawa, Ont. 425 pp.

THOMPSON, A. J. AND S. M. MONCRIEFF. 1982. Prediction of bud burst in Douglas-fir by degree-day accumulation. Can. J. For. Res. 12:448-452.

VAN WAGNER, C. E. 1967. Seasonal variation in moisture content of Eastern Canadian tree foliage and the possible effect on crown fires. Canada, Dept. For. Rural Develop. Pub. 1204, Forestry Br., Ottawa, Ont. 15 pp.

WENDEL, G. W. AND T. G. SHOREY. 1962. Seasonal moisture fluctuations in four species of Pocosin vegetation. USDA For. Serv. Sta. Pap. 147, Southeastern For. Exp. Sta., Asheville, NC. 9 pp.

YANCIK, R. F. AND P. J. ROUSSOPOULOS. 1982. User's guide to the National Fire Occurrence Data Library. USDA For. Serv., Rocky Mountain For. & Range Exp. Sta., Ft. Collins, CO. 25 pp.

A Markov Chain Model of a Forest Fire Danger Rating Index

D.L. MARTELL
Faculty of Forestry
University of Toronto
Toronto, Ontario

Abstract

This paper describes how a Markov chain model can be used to model day to day changes in the Fire Weather Index component of the Canadian Forest Fire Weather Index System. The paper also illustrates how such models can be incorporated into optimization models and used to help allocate fire management expenditures over the course of a fire season.

Résumé

Le présent article décrit comment un modèle du processus de Markov peut servir à modéliser les modifications quotidiennes de l'Indice Forêt-Météo une composante de la Méthode canadienne d'évaluation des dangers d'incendie forêt. L'article illustre également comment de tels modèles peuvent être incorporé à des modèles d'optimisation et contribuer à l'affectation des crédits de protection contre les incendies au cours de la saison des feux.

Introduction

The Fire Weather Index (FWI) is one of the components of the Canadian Forest Fire Weather Index (FWI) System. It is designed to be a numerical rating of fire intensity and is often used as a general measure of fire danger for planning purposes. This paper describes the development and testing of a Markov chain model of day to day changes in the FWI. We begin with a very brief overview of Markov chain theory and present a rationale for the use of a Markov model for the FWI. We then describe some of the statistical testing procedures associated with the development and testing of Markov chain models and present the results of an analysis of 26 years of fire weather data observed at three fire weather stations in the province of Ontario. We briefly outline how such models can be used for fire management planning purposes and conclude with a brief discussion of the value of the Markov approach and future research requirements.

Markov Chains and Fire Weather

Fire danger rating indices are usually designed to track some important aspect of the fire environment (e.g., forest fuel moisture or potential fire intensity) with a function that relates the current day's index to the previous day's index and weather (e.g., relative humidity and rainfall) observed during part or all of the intervening time period. They are usually measured on continuous scales and classified into discrete categories (e.g., low, high, or extreme fire danger rating classes) for management purposes. It is therefore reasonable to assume that one can model day to day changes in the fire danger rating index class as a discrete parameter stochastic process $\{X_n, n=1,2,..\}$ where the random variable X_n is the state (i.e., the fire danger class) of the system on day n. Furthermore, the mathematical structure of most fire danger rating indices is such that it is appropriate to consider modelling them as Markov chains with finite state spaces.

Suppose some fire danger rating index can be in one of m classes each day, and $X_n=i$ indicates the system is in class i on day n. A Markov chain of order 1 has the property that the conditional probability distribution of X_{n+1} (i.e., the state of the system on day n+1) given $X_1, X_2,...,X_n$ depends only on X_n. This Markov property can be expressed mathematically as

$$P\{X_{n+1}=j|X_1=i_1,X_2=i_2,...,X_n=i\} = P\{X_{n+1}=j|X_n=i\} \qquad (1)$$

for n = 1,2,... and every sequence $i_1,i_2,...,i,j$.

A Markov chain of order 1 is characterized by its transition probability matrix P, and $P_{i,j}$, the element in the ith row and jth column of P, is the probability that the system (e.g., the fire danger rating index class) will be in state j tomorrow, given that it is in state i today.

$$P = \begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1m} \\ P_{21} & P_{22} & \cdots & P_{2m} \\ . & . & & . \\ . & . & & . \\ P_{m1} & P_{m2} & \cdots & P_{mm} \end{bmatrix}$$

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

A Markov chain of order 2 is one in which the conditional probability distribution of the state of the system tomorrow depends on the state of the system today and yesterday. In general, a Markov chain of order r is one in which the conditional probability distribution of the state of the system tomorrow depends on the state of the system during the past r days.

Both homogeneous and non-homogeneous Markov chains have been used to model sequences of wet and dry days (see for example, Gabriel and Neumann (1962), Gates and Tong (1976), and Stern and Coe (1984)). Stern and Coe (1984) point out that the choice of an appropriate order has been discussed extensively and suggested the decision is site specific.

Several authors have addressed the use of Markov chains to model day to day changes in fire danger rating indices for fire management planning purposes. Kourtz (1970) used historical data for a forested area in Idaho and Montana to model thunderstorm day occurrence as a first order Markov chain and day to day changes in a spread index class variable as a second order Markov chain, but did not report the results of statistical tests of the validity of either model. Martell (1971) used a first order Markov chain to model day to day changes in the average burning index across the Ontario Ministry of Natural Resources' Northwestern Region, but did no statistical testing of the validity of his model. Greulich (1976) used likelihood ratio statistical test results to support his decision to use a first order Markov chain to model day to day changes in the brush burning index class at two fire weather stations located in the California Division of Forestry's District 1.

A Markov Chain Model for the FWI

The FWI is one of several components of the Canadian Forest Fire Weather Index System which is described by Van Wagner (1987). The FWI includes three basic moisture codes that serve as numerical ratings of the moisture content of three different components of a model forest fuel complex; the Fine Fuel Moisture Code (FFMC), the Duff Moisture Code (DMC), and the Drought Code (DC). Each day's FFMC is based on the previous day's FFMC and noon observations of temperature, relative humidity, and wind speed, and the 24 hour rainfall. The FFMC thus provides a running "inventory" of the moisture content of the fine fuels and is designed such that the current day's FFMC is closely related to the previous day's FFMC. The DMC and DC are also designed to reflect the moisture content of components of the model fuel complex and are based in part, on the previous day's DMC and DC respectively. It is therefore reasonable to assume that the day to day changes in the FFMC, DMC, and DC can be modelled as Markov chains.

The Initial Spread Index (ISI), which is designed to be a numerical rating of the spread rate of a fire, is a function of current day's FFMC and the noon hour wind speed. The Buildup Index (BUI) is a relative measure of the amount of fuel available for combustion and is a function of the current day's DMC and DC. They in turn, are used to compute the FWI each day. The Ontario Ministry of Natural Resources (OMNR) uses the classification scheme described in Table 1 to classify each day as having a nil, low, moderate, high, or extreme FWI. Given these relationships and the fact that precipitation can be modelled as a Markov process, it is reasonable to assume that it is possible to model day to day changes in the FWI class as a Markov chain.

Table 1. Fire Weather Index classification scheme used in Ontario.

Range	FWI Class
$FWI = 0$	Nil
$0 < FWI \leq 4$	Low
$4 < FWI \leq 11$	Moderate
$11 < FWI \leq 23$	High
$23 < FWI$	Extreme

Statistical Tests for Markov Chains

In order to develop a Markov chain model of day to day changes in the FWI class one must:

1. determine the extent to which the process is homogeneous with respect to time;
2. estimate the state transition probabilities (i.e., the elements of the probability matrix P) and
3. decide upon the order of the Markov chain.

It is reasonable to assume that the elements of the probability matrix P vary over the course of the season. One way of dealing with that variation is to develop a set of functions that relate the elements of P to time (see for example Stern and Coe 1984). However, that approach is not practical when dealing with an FWI class variable that can be in one of five states each day.

We chose instead, to partition the fire season into three subseasons, and to assume that P was homogeneous with respect to time within each subseason. One way to identify potentially good subseasons is to plot estimates of one or more of the elements of P over time. We chose the simpler route of plotting one-week

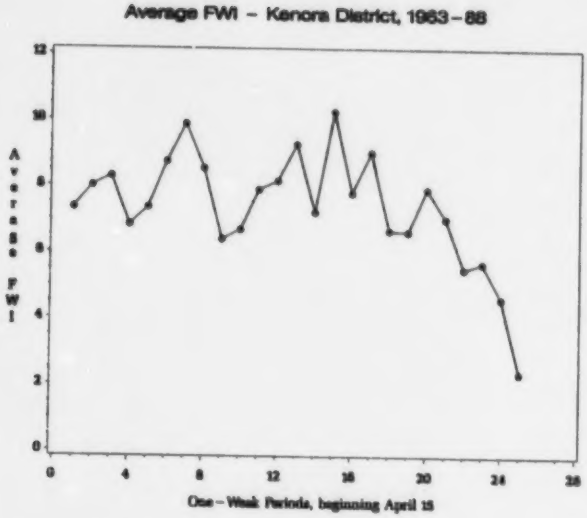


FIG 1. Plot of the weekly average Fire Weather Index at the Kenora fire weather station, based on 1963 through 1988 data. Each point on the graph represents an average based on 7 days and 26 years of data.

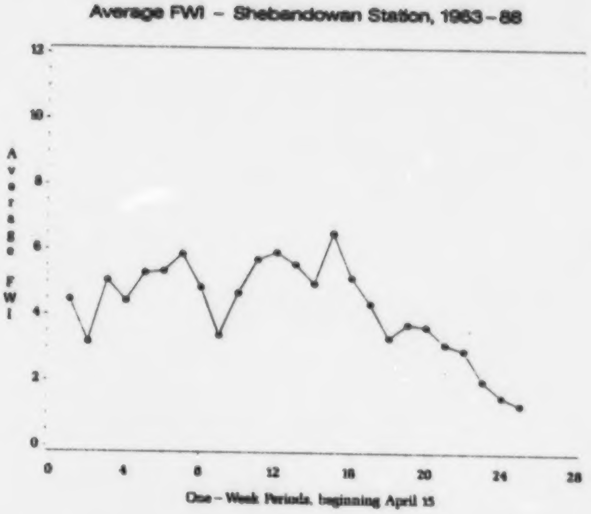


FIG 2. Plot of the weekly average Fire Weather Index at the Shebandowan fire weather station, based on 1963 through 1988 data. Each point on the graph represents an average based on 7 days and 26 years of data.

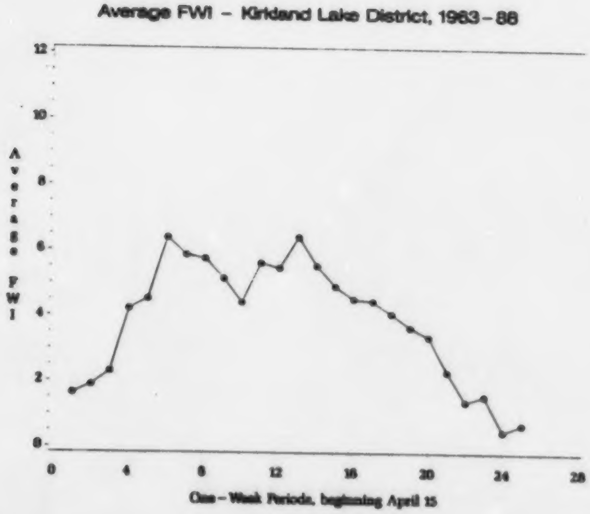


FIG 3. Plot of the weekly average Fire Weather Index at the Kirkland Lake fire weather station, based on 1963 through 1988 data. Each point on the graph represents an average based on 7 days and 26 years of data.

averages of the FWI over time, as shown in Figures 1, 2, and 3. Given these results, we decided to partition the fire season into the three subseasons described in Table 2, which were used in an earlier fire occurrence prediction study in Ontario (Martell et al. 1987). The Spring subseason includesperiods 3 through 8, the Early summer season includes periods 9 through 15, and the Summer season begins with period 16 and ends with period 22.

Table 2. Classification scheme that was used to partition the fire season into three subseasons.

Subseason	Dates
Spring	April 29 - June 9
Early summer	June 10 - July 28
Summer	July 29 - Sept. 15

Suppose one has observed a total of n transitions in a homogeneous Markov chain of order 1 with m states. Bhat (1984, pp. 137-140) shows that the maximum likelihood estimates of the elements of the probability matrix P, are

$$P_{ij} = \frac{n_{ij}}{n_i}$$

where n_{ij} denotes the observed number of transitions from state

i to state j $(i,j = 1,2,\ldots,m)$,

$\sum_{j=1}^{m} n_{ij} = n_i$, and $\sum_{i=1}^{m} n_i = n$.

We used the likelihood ratio test procedure described by Bhat (1984, pp. 142-144) to decide upon the order of the FWI Markov chain. Suppose the FWI Markov chain is of the order 2 and let P_{ijk} denote the probability that the FWI moves from state j to state k, given that it entered state j from state i.

The maximum likelihood estimate of P_{ijk} is given by:

$$\hat{P}_{ijk} = \frac{n_{ijk}}{n^{*}_{ij}}$$

where n_{ijk} denotes the observed number of transitions from state i, to state j and then state k, and n_{ij} equals $\sum n_{ijk}$.

Let H_o denote the null hypothesis that the FWI Markov chain is of order 1, and H_A the alternative hypothesis that it is of order 2. The null hypothesis can be expressed as

$$H_0\text{: } P_{ijk} = P_{jk} \qquad (i,j,k = 1,2,\ldots,m).$$

Bhat (1984) presents the following likelihood ratio test statistic (which we denote by $S_{1,2}$) which has a X^2 distribution with $m(m-1)^2$ degrees of freedom when H_0 is true.

$$S_{1,2} = 2\sum_{i,j,k} n_{ijk} \ln\left[\frac{n_{ijk}}{n^{*}_{ij}} \cdot \frac{n_i}{n_{ij}}\right]$$

The number of degrees of freedom is reduced by d where d denotes the number of state transition probability estimates P_{ij} that are zero. Thus H_0 is rejected if $S_{1,2}$ is greater than X^2_α for $m(m-1)^2$ - d degrees of freedom where α denotes the level of significance of the test.

As Bhat (1984) explains, the likelihood ratio test procedure can be generalized to consider:

H_{r-1}: the Markov chain is of order r-1

H_r : the Markov chain is of order r.

The likelihood ratio test statistic (which we label $S_{r-1,r}$) has a X^2 distribution with $m^{r-1}(m-1)^2$ less the number of zeroes in the estimated r-1 order transition probability estimates, if H_{r-1} is true.

Results

The results of an analysis of 26 years (1963-88) of fire weather data observed at the Kenora weather station are presented in Table 3. Table 3 contains the likelihood ratio test statistics and corresponding degrees of freedom for tests concerning Markov chains of orders 0, 1, and 2 within each subseason. We tested the null hypotheses at both 0.01 and 0.05 levels of significance. Those results indicate day to day changes in the FWI class can be modelled as a Markov chain of order 1 during the Spring and Early summer subseasons. However, the test results suggest a second order model is more appropriate for the Summer subseason.

The results for the Shebandowan and Kirkland Lake weather stations are presented in Tables 4 and 5 respectively. Those test results differ slightly from the Kenora results inasmuch as Markov chains of order 1 were found to be best for all three subseasons for both the Shebandowan and Kirkland Lake weather stations.

A Markov chain of order 1 and 5 FWI classes leads to a Markov chain with 5 states and a transition probability matrix with 25 elements to be estimated. A Markov chain of order 2 and 5 FWI classes would result in 25 states (i.e., the FWI class on the last 2 days) and a transition probability matrix with 625 elements to be estimated. These practical considerations coupled with the statistical test results presented in

Tables 3 through 5 suggest it is reasonable to limit ourselves to Markov chains of order 1 for modelling day to day changes in the FWI class.

Table 3. Markov chain analysis of the FWI class fire weather data observed at the Kenora fire weather station during the 1963 through 1988 fire seasons.

Likelihood Ratio Statistics	Degrees of Freedom	$X^2_{.01}$	Reject H_{r-1}	$X^2_{.05}$	Reject H_{r-1}
Spring (April 29 - June 9)					
$S_{0,1} = 643.0$	16	32.0	yes	26.3	yes
$S_{1,2} = 90.0$	79	111.0	no	101.0	no
$S_{2,3} = 268.9$	370	436.1	no	416.0	no
Number of two-day transitions: 1090					
Early Summer (June 10 - July 28)					
$S_{0,1} = 673.1$	16	32.0	yes	26.3	yes
$S_{1,2} = 82.2$	79	111.0	no	101.0	no
$S_{2,3} = 265.3$	379	445.9	no	425.5	no
Number of two-day transitions: 1326					
Summer (July 29 - September 15)					
$S_{0,1} = 730.5$	16	32.0	yes	26.3	yes
$S_{1,2} = 119.4$	79	111.0	yes	101.0	yes
$S_{2,3} = 255.3$	369	435.0	no	414.9	no
Number of two-day transitions: 1298					

Table 4. Markov chain analysis of the FWI class fire weather data observed at the Shebandowan fire weather station during the 1963 through 1988 fire seasons.

Likelihood Ratio Statistics	Degrees of Freedom	$X^2_{.01}$	Reject H_{r-1}	$X^2_{.05}$	Reject H_{r-1}
Spring (April 29 - June 9)					
$S_{0,1} = 713.2$	16	32.0	yes	26.3	yes
$S_{1,2} = 86.0$	78	109.8	no	99.8	no
$S_{2,3} = 173.3$	349	413.3	no	393.7	no
Number of two-day transitions: 1110					
Early Summer (June 10 - July 28)					
$S_{0,1} = 678.6$	16	32.0	yes	26.3	yes
$S_{1,2} = 80.3$	79	111.0	no	101.0	no
$S_{2,3} = 189.5$	360	425.2	no	405.4	no
Number of two-day transitions: 1326					
Summer (July 29 - September 15)					
$S_{0,1} = 725.4$	16	32.0	yes	26.3	yes
$S_{1,2} = 69.6$	76	107.4	no	97.6	no
$S_{2,3} = 156.3$	343	406.7	no	387.3	no
Number of two-day transitions: 1309					

Table 5. Markov chain analysis of the FWI class fire weather data observed at the Kirkland Lake fire weather station during the 1963 through 1988 fire seasons.

Likelihood Ratio Statistics	Degrees of Freedom	$X^2_{.01}$	Reject H_{r-1}	$X^2_{.05}$	Reject H_{r-1}
Spring (April 29 - June 9)					
$S_{0,1} = 646.4$	16	32.0	yes	26.3	yes
$S_{1,2} = 97.6$	80	112.3	no	101.9	no
$S_{2,3} = 171.4$	357	422.0	no	402.2	no
Number of two-day transitions: 1048					
Early Summer (June 10 - July 28)					
$S_{0,1} = 683.5$	16	32.0	yes	26.3	yes
$S_{1,2} = 72.9$	79	111.0	no	101.0	no
$S_{2,3} = 200.8$	362	427.4	no	407.5	no
Number of two-day transitions: 1316					
Summer (July 29 - September 15)					
$S_{0,1} = 666.9$	16	32.0	yes	26.3	yes
$S_{1,2} = 72.7$	76	107.4	no	97.6	no
$S_{2,3} = 125.9$	344	407.8	no	388.4	no
Number of two-day transitions: 1248					

Markov Chain Models and Fire Management Planning

The transition probability matrix for the Spring subseason at the Kenora weather station is:

$$P = \begin{bmatrix} 0.60 & 0.29 & 0.10 & 0.01 & 0.00 \\ 0.21 & 0.29 & 0.38 & 0.11 & 0.01 \\ 0.19 & 0.08 & 0.38 & 0.30 & 0.05 \\ 0.14 & 0.08 & 0.19 & 0.45 & 0.14 \\ 0.10 & 0.05 & 0.06 & 0.31 & 0.48 \end{bmatrix}$$

The **P** matrix itself provides a considerable amount of information concerning day to day changes in the FWI class. For example, P_{ii} is the probability that the FWI class will persist in class i for at least n more consecutive periods, given that it is currently in class i. For example, in Kenora district, if the FWI is currently extreme during the Spring subseason, the probability that it will remain extreme for at least 3 more days is 0.48^3 or 0.11

One can also use P to determine π, the steady state probability vector, the j^{th} component of which is the steady state or long run probability that the FWI class is in state j. π is specified by solving the following set of linear equations.

$$\pi_j = \sum_{i=1}^{m} \pi_i p_{ij} \qquad j = 1,2,\ldots,m$$

$$\sum_{j=1}^{m} \pi_j = 1$$

The solution for the Spring subseason in Kenora district is $\pi = (0.30, 0.18, 0.23, 0.21, 0.08)$. This indicates that the FWI class in Kenora is nil on roughly 30% of the days during the Spring subseason.

One important aspect of forest fire management planning is the fact that what happens during a particular day is often influenced by the cumulative influence of the fireloads that the suppression organization has had to contend with during the past few days. Markov chains make it relatively easy to incorporate such dependencies in fire management planning models. Consider for example, fire fighter needs during fire flaps (i.e., periods during which the fire danger is elevated and large numbers of fires occur each day). Each day, a small proportion of fires will escape initial attack and become extended attack fires that demand large amounts of suppression resources for several days. The proportion of fires that escape each day will depend upon many factors including the fire danger rating index and number and quality of initial attack crews available that day. The probability that a fire will escape will usually increase as the duration of the fire flap increases, crews and other suppression resources become less readily available, and crews that are available are overworked, and in many cases supplemented by "auxiliary" crews made up of forest workers with some fire fighting training but relatively little practical fire fighting experience. Planning models that treat each day independently do not capture the congestion and subsequent increased fire escape probability that are the essence of fire flaps, and their use would undoubtedly lead to under-estimates of initial attack crew needs.

A small number of authors have used Markov chain models of day to day changes in fire danger rating class variables to incorporate day to day dependencies in fire management planning models. Greulich (1976) used his brush burning index Markov chain model to develop a Markov Decision Process model designed to help decide how to allocate 5 air tankers to 3 home bases at the start of a fire season, and how to deploy them to those bases on a daily basis throughout the fire season. Boychuk and Martell (1988) assumed day to day changes in a fireload index based in part, on the FWI, could be modelled as a Markov chain, and incorporated that model in a larger Markov model that can be used to evaluate annual fire fighter hiring decisions.

Discussion

The test results for the Kenora, Shebandowan, and Kirkland Lake fire weather stations indicate it is reasonable to model day to day changes in the FWI class as a Markov chain of order 1. That is consistent with the results presented by Greulich (1976) who opted to use a first order Markov chain to model day to day changes in a brush burning index, despite the [illegible]t that his likelihood ratio test results suggested a [illegible]ond order model might have been more appropriate for one of two fire weather stations located in the California Division of Forestry's District 1.

Although the results presented in this paper can be used for fire management planning purposes, they highlight several issues that should be addressed in future studies. The question of time homogeneity should be more carefully investigated with a view to developing simple procedures to cope with non-homogeneous transition probabilities, particularly during the Summer subseason.

The choice of the five FWI classes described in Table 1 is somewhat arbitrary. Although practical problems make it necessary to group FWI values into a relatively small number of classes, the choice of categories should ultimately be determined by the management decisions and the structure of the system models in which the FWI Markov chain models are imbedded.

We limited our statistical analysis to the FWI but suggested it may be appropriate to model day to day changes in FFMC, DMC, and DC classes as Markov chains. Since fire management system models are by no means limited to the use of the FWI, the applicability of Markov models for precipitation and the other components should also be investigated.

Acknowledgements

This research was supported by the Natural Sciences and Engineering Research Council of Canada. I wish to thank the many Ontario Ministry of Natural Resources (OMNR) fire personnel, the Aviation & Fire Management Centre of the OMNR, and the Fire Research Unit of the Great Lakes Forestry Centre of Forestry Canada, Ontario Region, who observed, compiled and provided the fire weather data to me in computer readable form. I also wish to thank C. Hewitt and R. Davis who assisted with the development of the computer software used in this study, and the preparation of this paper.

Endnotes

[1] We are assuming that the transition probabilities do not vary over time (i.e., the process is time-homogeneous). For an introduction to Markov chain theory see for example, Bhat (1984), or Ross (1985).

References

BHAT, U.N. 1984. Elements of applied stochastic processes. John Wiley & Sons, Inc. New York.

BOYCHUK, D., AND D.L. MARTELL. 1988. A Markov chain model for evaluating seasonal forest fire fighter requirements. For. Sci. 34:647-661.

GABRIEL, K.R., AND J. NEUMANN. 1962. A Markov chain model for daily rainfall occurrence at Tel Aviv. Quart. J. Roy. Meteor. Soc. 88:90-95.

GATES, P., AND H. TONG. 1976. On Markov chain modeling to some weather data. J. Applied Meteor. 15:1145-1151.

GREULICH, F.E. 1976. A model for the seasonal assignment of air tankers to home bases under optimal expected daily traffic transfer/use rules. Ph.D. dissertation, University of California, Berkeley, CA.

KOURTZ, P.H. 1970. A cost-effectiveness analysis of a simulated airborne infrared forest fire detection system. Ph.D. dissertation, University of California, Berkeley, CA.

MARTELL, D.L. 1971. Optimization of airtanker operations in forest fire suppression. B.A.Sc. thesis, Department of Industrial Engineering, University of Toronto, Toronto, Ont.

MARTELL, D.L., S. OTUKOL, AND B.J. STOCKS. 1987. A logistic model for predicting daily people-caused forest fire occurrence in Ontario. Can. J. For. Res. 17: 394-401.

ROSS, S.M. 1985. Introduction to probability models. Third edition. Academic Press, Inc. New York.

STERN, R.D., AND R. COE. 1984. A model fitting analysis of daily rainfall data. J. Roy. Statist. Soc. A. 147, Part 1, pp. 1-34.

VAN WAGNER, C.E. 1987. Development and structure of the Canadian forest fire weather index. For. Tech. Rep. 35, Canadian Forestry Service, Ottawa.

Suitability of the Canadian Forest Fire Danger Rating System for Use in the Daxinganling Forestry Management Bureau Heilongjiang Province, China

T.J. LYNHAM AND B.J. STOCKS
Forestry Canada, Ontario Region, Great Lakes Forestry Centre
Sault Ste. Marie, Ontario

Abstract

The applicability of the Canadian Forest Fire Danger Rating System (CFFDRS) for use in predicting fire danger, fire behavior, and fire occurrence in the Daxinganling Forestry Management Bureau (DXALFMB) in northeastern China is discussed. Fire weather, fuel types, and fire occurrence patterns in the DXALFMB are compared with those of the Red Lake District of northwestern Ontario, an area located at approximately the same latitude as the DXALFMB, in which periods of extreme fire weather routinely result in very large and intense forest fires.

Ten years (1975-1984) of weather and fire occurrence records for five stations (Jiagedaqi, Xinlin, Tahe, Huma and Mohe) within the DXALFMB were collected. Similar data were compiled for one station in the Red Lake District of Ontario. Fuel conditions throughout the DXALFMB were observed in late 1985.

The five Chinese weather stations analyzed show similar weather trends throughout the fire season, both in terms of the weather variables measured (temperature, relative humidity, wind speed, and precipitation) and as reflected through the calculated codes and indices of the Canadian Forest Fire Weather Index (FWI) System. Fire weather, as reflected by the FWI System, is markedly more severe throughout the DXALFMB than in the Red Lake District, particularly in the spring period.

Fires in the DXALFMB, on average, are much larger in area than in the Red Lake District. This is primarily a result of the combination of extreme fire weather and cured grass fuels during the spring, but may also be a reflection of inadequate capabilities for detection and initial attack. A forest fire occurrence prediction model developed for use in Ontario by the Faculty of Forestry, University of Toronto, with the assistance of the Great Lakes Forestry Centre, Forest Fire Research Unit, shows promise for use in the DXALFMB.

Résumé

Le présent rapport examine l'applicabilité de la Méthode canadienne d'évaluation des dangers d'incendie de forêt (MCEDIF) pour prédire le danger de feu et le comportement et la fréquence des incendies dans le territoire du Bureau d'aménagement forestier de Daxinganling (BAFDAXL) dans le nord-est de la Chine. La configuration des conditions météorologiques propices aux incendies, des types de combustibles et de la fréquence des incendies du territoire du BAFDAXL sont comparées à celles du district de Red Lake, dans le nord-ouest de l'Ontario, une région située à peu près à la même latitude et où les périodes de conditions météorologiques extrêmement propices aux incendies provoquent régulièrement des incendies de forêt très gros et intenses.

Dix ans de relevés météorologiques (1975-1984) provenant de cinq stations (Jiagedagi, Xinlin, Tahe, Huma et Mohe) situées sur le territoire du BAFDAXL ont été réunis ainsi que les relevés de la fréquence des incendies pendant la même période. Des données semblables ont été compilées pour une station dans le district de Red Lake en Ontario. L'état des combustibles dans l'ensemble du territoire du BAFDAXL a été observé à la fin de 1985.

Les données des cinq stations météorologiques analysées laissent voir des tendances similaires des conditions météorologiques pendant toute la saison des feux, tant sur le plan des variables météorologiques mesurées (température, humidité relative, vitesse du vent et précipitations) que sur celui des codes calculés et des indices de la Méthode canadienne de l'Indice Forêt-Météo. Les conditions météorologiques propices aux incendies reflétées par l'Indice Forêt-Météo sont visiblement plus sévères dans l'ensemble du territoire du BAFDAXL que dans le district de Red Lake, particulièrement au printemps.

Les incendies faisant rage dans le territoire du BAFDAXL sont en moyenne beaucoup plus importants en superficie que dans le district de Red Lake, principalement en raison des conditions météorologiques extrêmement propices aux incendies qui se combinent à la présence de graminées séchées au printemps mais qui peuvent refléter des capacités inadéquates de détection des incendies et d'attaque initiale. Un modèle de prévision de la fréquence des incendies de forêt élaboré spécialement pour l'Ontario par la faculté de foresterie de l'Université de Toronto avec l'aide de l'Unité de recherche sur les incendies de forêt du Centre de foresterie des Grands Lacs semblerait pouvoir être utilisé dans le territoire du BAFDAXL.

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

Introduction

The largest and most commercially valuable expanse of natural forest in the People's Republic of China is located in the Daxinganling Forestry Management-bureau (DXALFMB), an area of northeastern China that covers the northernmost parts of Heilongjiang Province and the Inner Mongolia Autonomous Region (Fig. 1). The DXALFMB covers approximately 8.5 million ha, lies between 50° and 54° north latitude and 121° and 127° east longitude, and is separated from the Union of Soviet Socialist Republics on the north and east by the Heilonjiang (Amur) River.

Forest fires have been a major problem in this part of China for many years, with the result that an estimated 2-3% of the forested area of Heilongjiang Province is lost to fire annually. Extreme fire weather and fuel conditions, in combination with an inadequate fire management capability, has resulted in the burning of vast areas by the relatively few fires that occur in this region. To address this problem the Government of China signed an agreement with the Canadian International Development Agency (CIDA) in 1984, under which the Ontario Ministry of Natural Resources (OMNR) would provide technical expertise to the Chinese for a 5-year period. The goal of this agreement was to develop a model forest fire management system in the DXALFMB by training Chinese personnel and improving communication, detection, and suppression capabilities. Forestry Canada (FORCAN) personnel were asked to evaluate the suitability of the Canadian Forest Fire Danger Rating System (CFFDRS) (Anon. 1987) for use in the DXALFMB. This 5-year CIDA project, which was to terminate in 1989, has been extended for an additional 2-year term, after a setback that resulted from the large forest fire of May 1987 (Fig. 1) in the northern part of the area.

This report evaluates applicability and suitability of the CFFDRS in predicting fire occurrence and fire behavior in the DXALFMB. Fire weather, fuel types, and fire occurrence patterns in the area are compared with those in the Red Lake District of northwestern Ontario, an area located at approximately the same latitude. This area of Ontario routinely experiences periods of extreme fire weather that result in very large and intense forest fires.

A fire occurrence prediction model, developed by the Faculty of Forestry, University of Toronto, was tested for potential use in the DXALFMB and the results are described. This report also attempts to summarize the best information available on the behavior of the large Chinese fire of May 1987. The weather associated with this fire is examined within the larger context of the severe fire weather problems that exist in this part of China.

Ten years of weather records (for the period from 1 April to 30 November, 1975 to 1984) for five stations (Jiagedaqi, Xinlin, Tahe, Huma and Mohe) within the DXALFMB were collected along with fire occurrence records for the same period. Similar data were compiled for one station in the Red Lake District of Ontario, where weather records covered the period from 15 April to 30 September, 1975 to 1984. Weather observations were taken at 1100 hr Local Standard Time (LST) in the DXALFMB and at 1200 hr LST in Red Lake.

Fuel conditions throughout the DXALFMB were observed in late 1985 when B.J. Stocks visited the area for a number of weeks. Both authors are quite familiar with the fuel types of northwestern Ontario.

Physiography and Vegetation

The DXALFMB is a generally hilly area dominated by the Greater Khingan Mountain Range, where elevations vary from 200 to 1500 m above mean sea level and slopes are normally less than 15%. Rivers are generally shallow and surrounded by open grassland. There are very few natural lakes. Brown podzolic forest soils on the slopes grade into dark brown forest soils and bog soils in the wide valley bottoms. The montane coniferous forests that once covered all of this area consisted primarily of pure larch (Larix gmelinii) and birch (Betula spp.). As a result of over-harvesting and repeated extensive wildfire, natural larch stands have virtually disappeared in the southern portion of the area and have been replaced by oak and birch scrublands and almost continuous grasslands with very little organic material. In the northern portion of the area, pure larch stands of various ages predominate; the understory vegetation and the forest floor organic layers are very similar to those of the Canadian boreal forest. The mosaic of vegetation patterns and the presence of numerous fire scars indicate a history of fire activity in this area.

The Red Lake District of northwestern Ontario also lies between 50° and 54° north latitude. The elevations range between 200 and 500 m above sea level and the topography is gently rolling. Extensive stands of even-aged jack pine (Pinus banksiana Lamb.) and black spruce (Picea mariana (Mill.) B.S.P.) predominate and attest to the repeated occurrence of large-scale stand-replacing wildfires. Soils are shallow over bedrock and organic layers (primarily moss) are thin.

General Climatology

Climatic normals (precipitation and temperature) for the 1951-1980 period for both the DXALFMB area (Anon. 1981) and the Red Lake District (Anon. 1982a,b) are presented in Figures 2 and 3. Summer temperatures in both locations are similar. Spring and fall periods, and particularly the winter months, are much colder in the DXALFMB. The Red Lake area has an average growing season of 165 days whereas the DXALFMB has a growing season of 130 days.

Precipitation is high in the summer and low throughout the remainder of the year in the DXALFMB, and annual precipitation is approximately 100 mm less than in the Red Lake District. This difference occurs during the winter months. Snowfall accounts for 17% of total

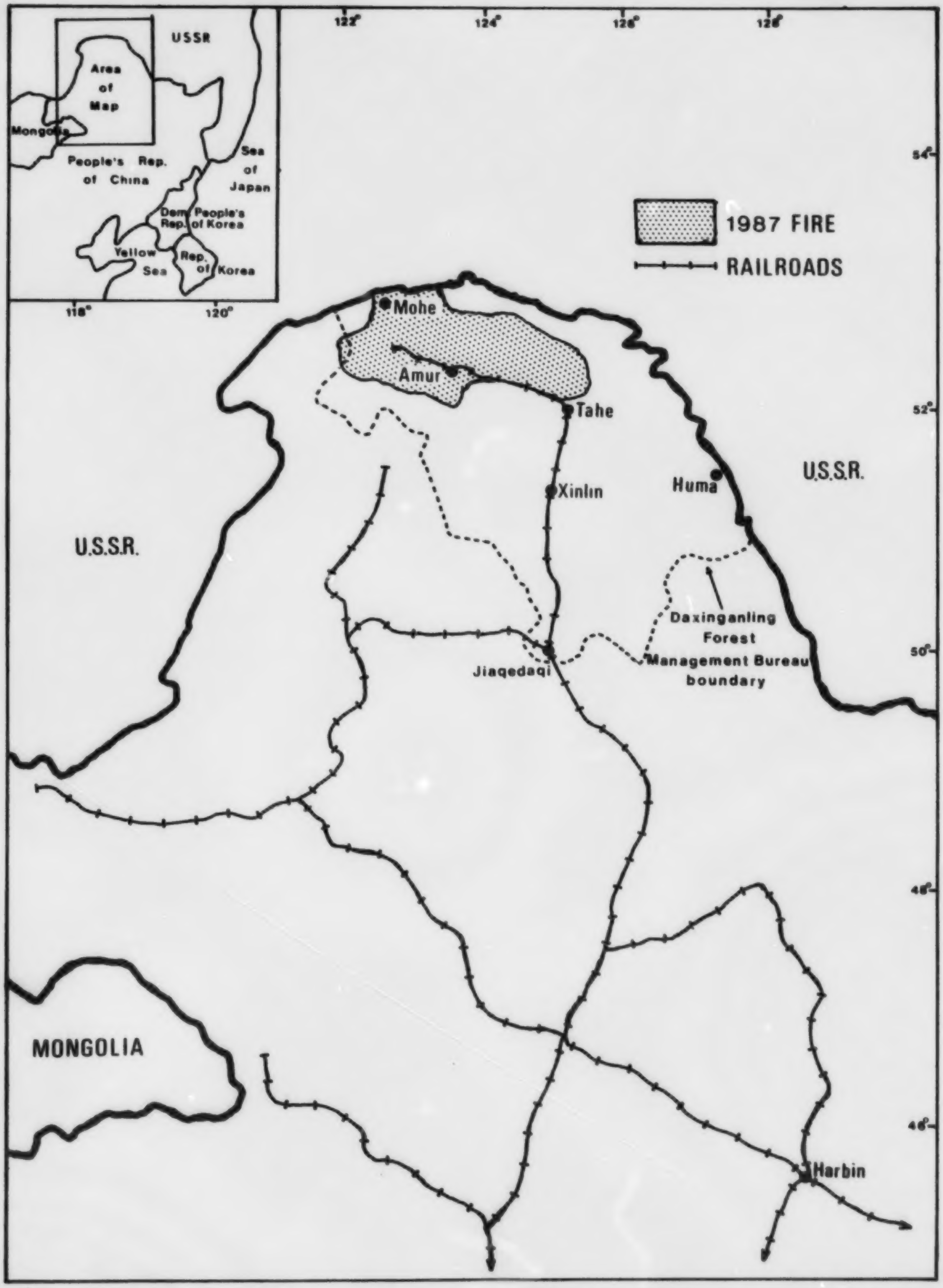

USSR
Area of Map
Mongolia
People's Rep. of China
Sea of Japan
Dem. People's Rep. of Korea
Yellow Sea
Rep. of Korea
118°
120°
122°
124°
126°
128°
54°
52°
50°
48°
46°
1987 FIRE
RAILROADS
Mohe
Amur
Tahe
Xinlin
Huma
U.S.S.R.
U.S.S.R.
Daxinganling Forest Management Bureau boundary
Jiaqedaqi
MONGOLIA
Harbin

FIG 1. General location of the Daxinganling Forestry Management Bureau and the Great China Fire of 1987, within the Heilongjiang Province, northeastern China.

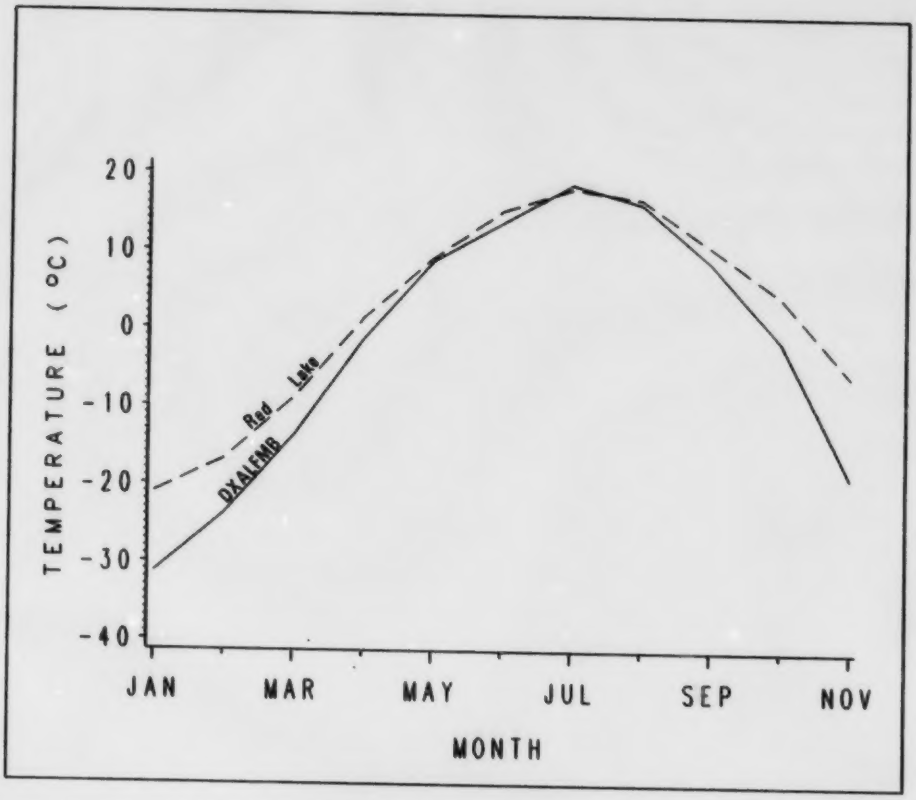


FIG 2. Temperature normals for the Daxinganling Forestry Management Bureau and the Red Lake District, 1951-1980.

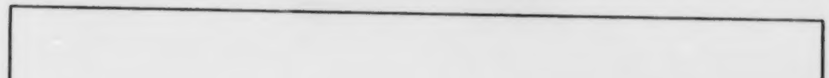


FIG 3. Precipitation normals for the Daxinganling Forestry Management Bureau and the Red Lake District, 1951-1980.

precipitation in the DXALFMB versus 31% in the Red Lake District.

Fire Weather and Fire Activity

Preliminary analysis of graphs of temperature, precipitation, relative humidity, and wind speed, averaged weekly for the five Chinese weather stations, revealed trends that are remarkably similar for each station. These data were used to calculate one set of general weather trends for the DXALFMB (Fig. 4a-4d). Corresponding data for Red Lake, which come from one station, are presented in Figures 5a-5d. Trends in the Red Lake weather parameters are significantly different from those of the DXALFMB. Although the spring period in the Red Lake District is characterized by low precipitation, low relative humidity and high wind speeds, the same factors exist during this period in a much more pronounced manner in the DXALFMB. Extremely high wind velocities and low relative humidities occur at the DXALFMB stations during the months of April and May, in conjunction with almost negligible precipitation and gradually warming temperatures. During the summer months, rainfall increases dramatically, relative humidity levels are much higher and temperatures are warmer, and wind speeds decrease significantly. The fall period, which begins in early September, is characterized by quickly declining levels of precipitation and relative humidity, increasing wind speeds and gradually decreasing temperatures. Fall fire weather in the DXALFMB is important but does not approach the severity of that in the spring period. In the Red Lake District, fire weather severity decreases during the summer and fall periods as precipitation levels remain generally steady, relative humidities increase, and wind speeds decrease.

Statistics on fire occurrence and area burned for the DXALFMB, averaged for the 1975-1984 period, are presented in Figures 6a and 6b. The most striking feature of these graphs is the strong bimodal nature of the fire season in the DXALFMB as a result of frequent large spring fires, and less frequent, smaller fall fires. There is no record of summer fires in the area. This seasonal trend is primarily attributable to the severe fire weather and dry fuels common to both the spring and fall periods, especially during the months of April and May. The abnormally high area-burned for week 6 in Figure 6(b) is a result of a single 669,415ha fire that occurred on 9 May 1977. Heavy precipitation and warmer temperatures, with resultant flushing of vegetation, preclude fires during the summer months. Many spring fires, primarily in grass fuels, occur when temperatures are quite low.

Figures 7a and 7b illustrate fire activity for the Red Lake District averaged over the 1975-1984 period. The seasonal fire occurrence pattern differs dramatically from that of the DXALFMB; fires occur continuously throughout the fire season and peak during the summer months. Area-burned values vary throughout the spring and summer. The high value for week 22 in the Red Lake District reflects the occurrence of a number of large fires early in September of 1983.

Fire statistics for the 1975-1984 period, for both the DXALFMB and the Red Lake District, are presented in Table 1 for purposes of comparison. Despite the fact that Red Lake District had more than twice as many recorded fires, many of which were not acted upon because of their remote location, the average fire size in the DXALFMB is seven times larger than that in Red Lake. This is attributable in part to the cured grass fuel type in the DXALFMB but may also reflect inadequacies in detection and initial attack.

Table 1. Comparison of the DXALFMB* and the Red Lake District fire statistics for the 1975-1984 period.

	Area protected (ha)	No. fires	Area burned (ha)	Annual % area burned	Average fire size (ha)
DXALFMB*	8,452,300	452	1,886,454	2.2	4,174
Red Lake	6,410,500	1,068	647,330	1.0	606

*Daxinganling Forest Management Bureau.

Canadian Forest Fire Weather Index System

Histograms for the Fine Fuel Moisture Code (FFMC), Initial Spread Index (ISI) and Fire Weather Index (FWI) components of the FWI System (Anon. 1984) for the entire fire season in the DXALFMB and the Red Lake District are shown in Figures 8a-8f. These three components of the FWI System are known to react quickly to changes in fire weather, and thereby provide an important means of comparing fire weather severity between the two locations. The charts demonstrate the high degree of fire weather severity in the DXALFMB. FFMC values of 91 and higher are generally considered extreme in northwestern Ontario. From data for the whole fire season, 13% of days in the DXALFMB fall into the extreme class (Fig. 8a). In comparison, only 6% of days in the Red Lake District fall into the extreme class (Fig. 8d). The severity of fire weather in the DXALFMB is even more pronounced if only the spring period is examined (Fig. 9a-9f). In the spring, which represents the peak period of fire activity in the DXALFMB, 30% of the days fall into the extreme class of the FFMC (Fig. 9a). In Red Lake District, which often has one of the most severe spring fire seasons, in Ontario, only 12% of the days fall into the extreme class of the FFMC (Fig. 9d).

The severity of the fire weather situation in the DXALFMB is further reinforced by examining the ISI and FWI values. In spring, 27% of days fall into the extreme class of the ISI (Fig. 9b) and 25% of days have FWI values greater than 21 (Fig. 9c). Clearly, the most striking feature of the DXALFMB is the frequent occurrence of severe short-term fire weather.

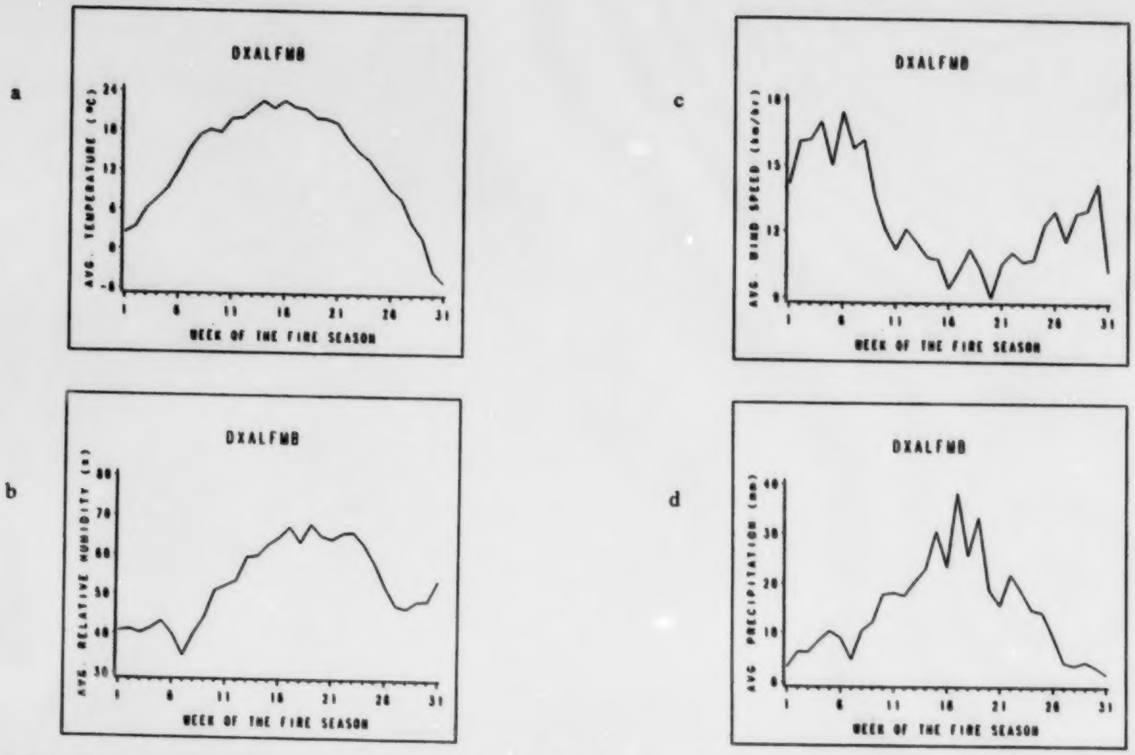


FIG 4. Weather data (average from five stations) for the Daxinganling Forestry Management Bureau for the period 1975-1984.

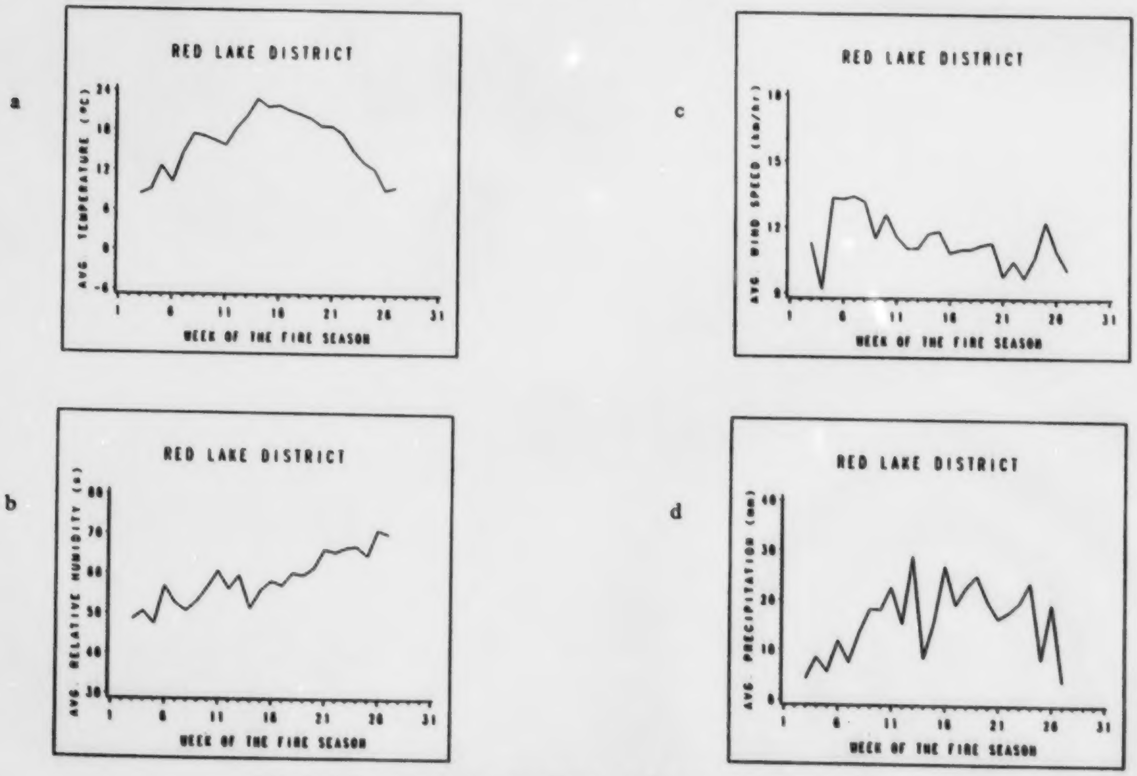
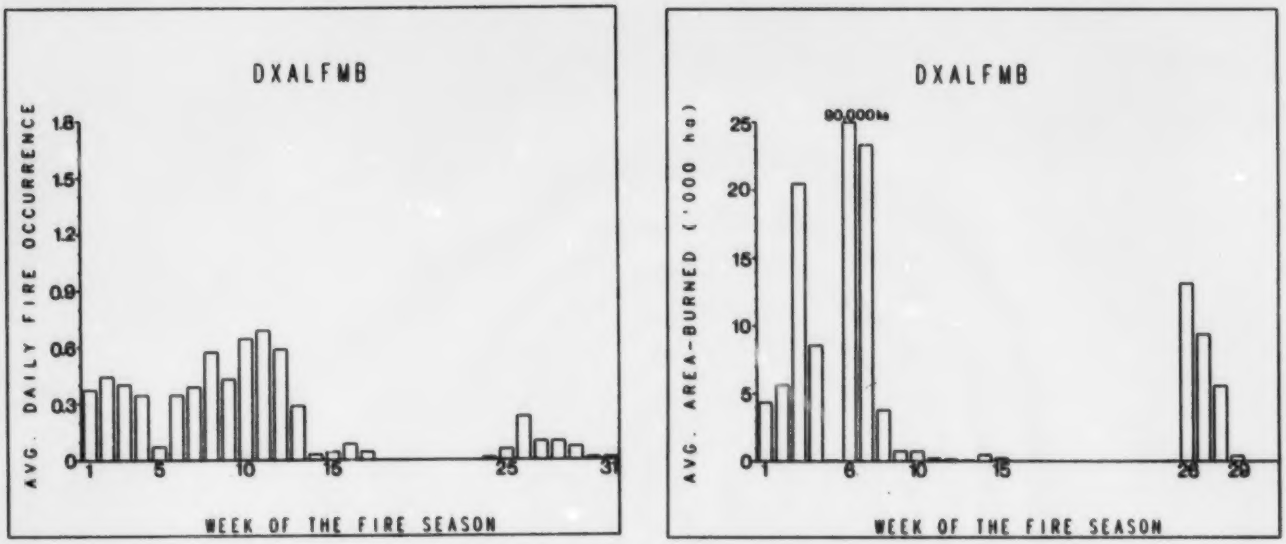


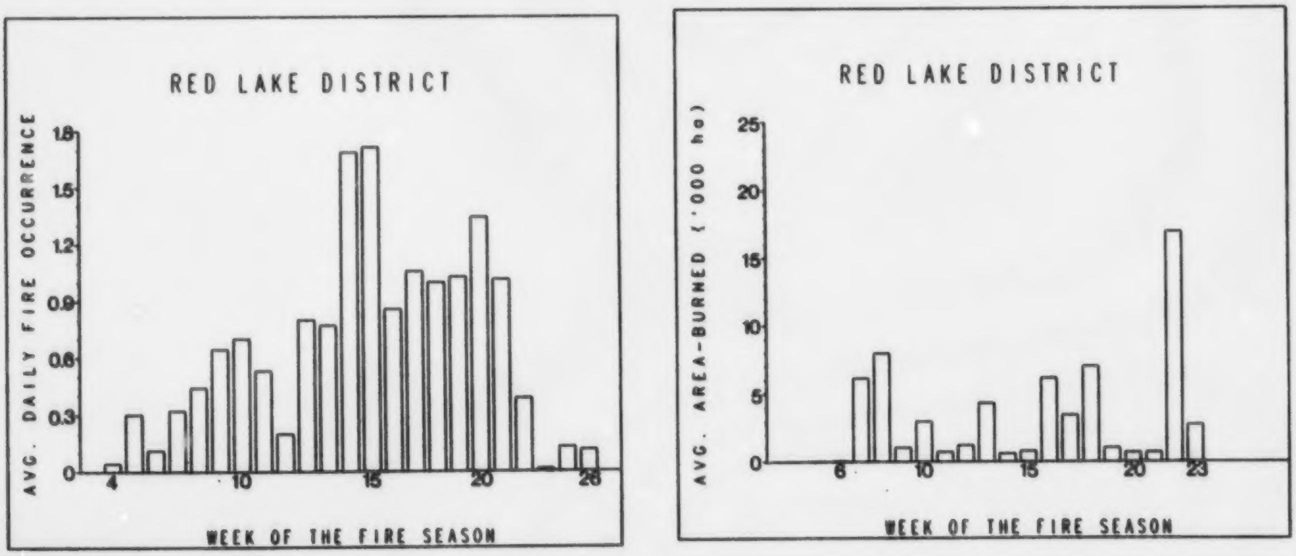
FIG 5. Weather data for the Red Lake District for the period 1975-1984.



a

b

FIG 6. Fire occurrence (a) and area-burned (b) statistics (average from five stations) for the Daxinganling Forestry Management Bureau for the period 1975-1984.



a

b

FIG 7. Fire occurrence (a) and area-burned (b) statistics for the Red Lake District for the period 1975-1984.

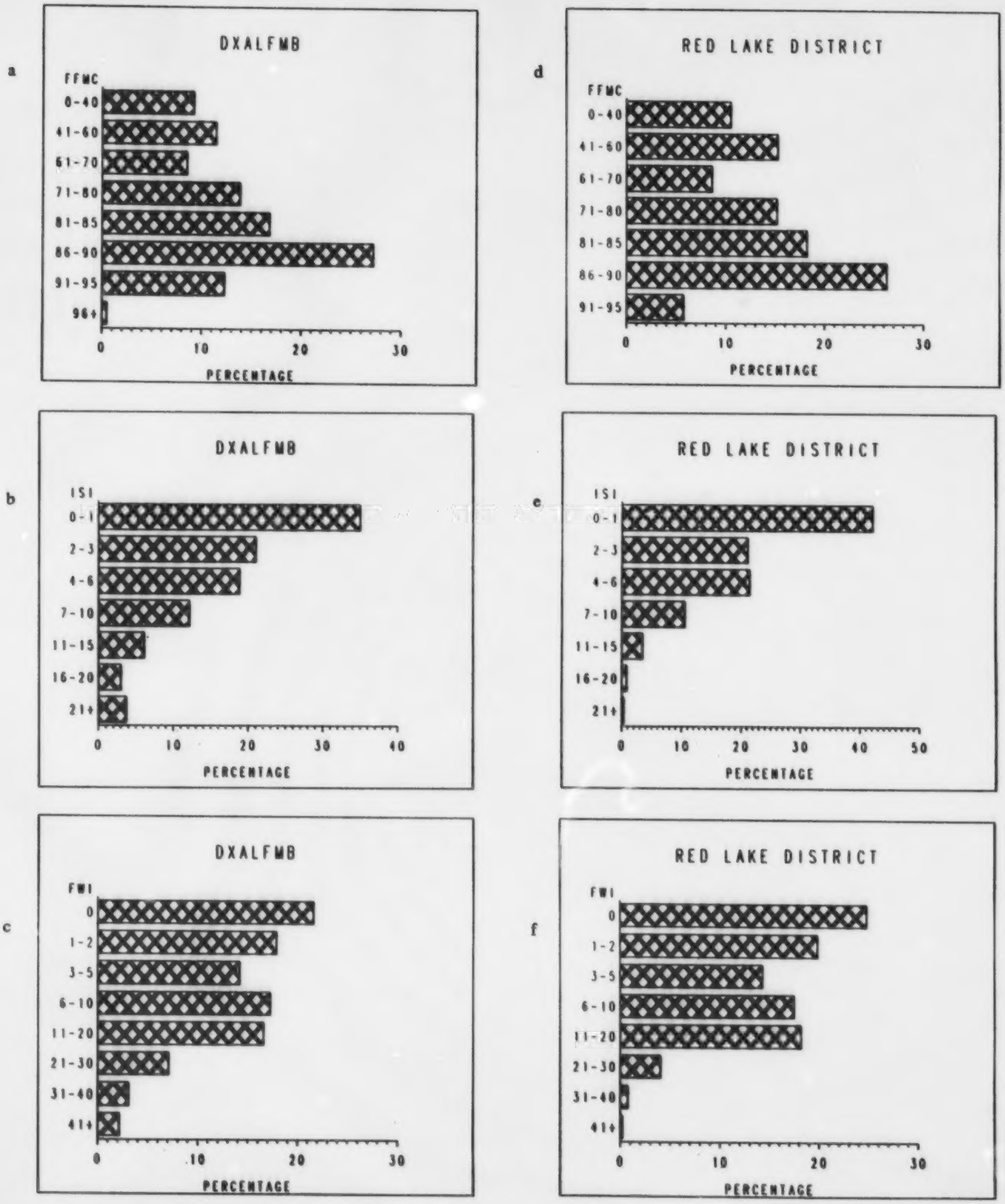


FIG 8. Percent occurrence of the Fine Fuel Moisture Code (FFMC), Initial Spread Index (ISI), and Fire Weather Index (FWI) for the entire fire season in the Red Lake District and the Daxinganling Forest Management Bureau (DXALFMB) for the period 1975-1984.

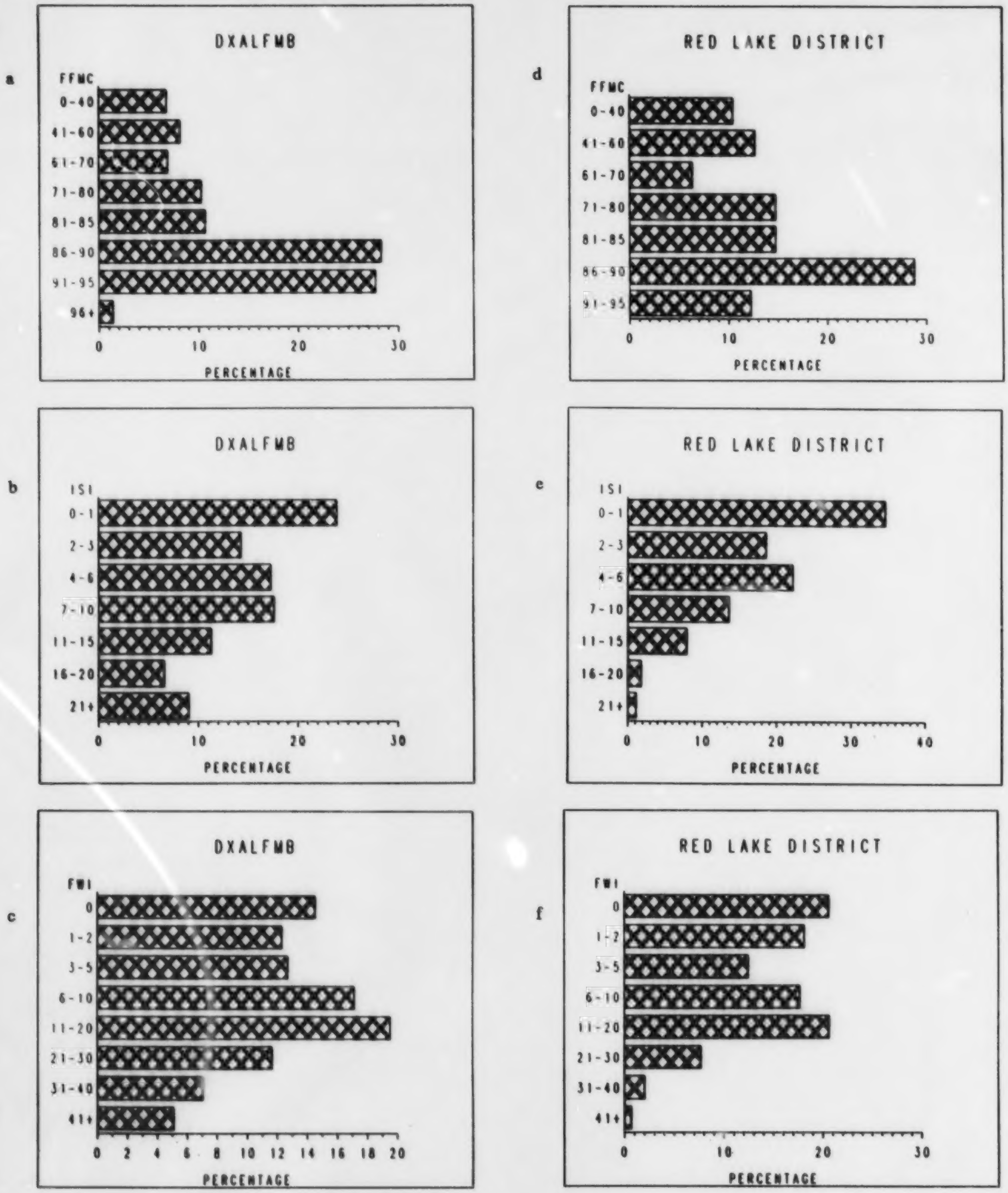


FIG 9. Percent occurrence of the Fine Fuel Moisture Code (FFMC), Initial Spread Index (ISI), and Fire Weather Index (FWI) for the spring season in the Red Lake District and the Daxinganling Forest Management Bureau (DXALFMB) for the period 1975-1984.

Forest Fire Occurrence

Forest fire occurrence records from the DXALFMB indicate that there were 452 fires during the 10-year period of this study. Of these, 104 fires (23%) were caused by lightning, 209 (46%) were caused by people and 139 (31%) were attributed to unknown causes. Ten years of lightning and people-caused fire occurrence data are shown in Figure 10, with fires of unknown origin being treated as people-caused fires. These plots show the predominance of people-caused forest fires in the southern sector. This is probably because the Jiagedaqi area has the highest population density in the DXALFMB.

Another notable concentration of people-caused fires occurs though the center of the project area, in a north-south direction. This is in close proximity to the main railway line. Data from the fire reports confirm that railway fires account for many of these fires. The source of ignition for most railway fires is either brake-shoe material or emissions from the smokestacks on the train engines.

Forest fires of industrial origin are prominent in the northern sectors, where logging operations dominate activity in the larch forests. Other important people-caused fires include those started by smoking material, or from campfires of mushroom or blueberry pickers, bee keepers, hunters and fishermen.

The fire data (Fig. 10) show that lightning fires dominate in the northern half of the DXALFMB.

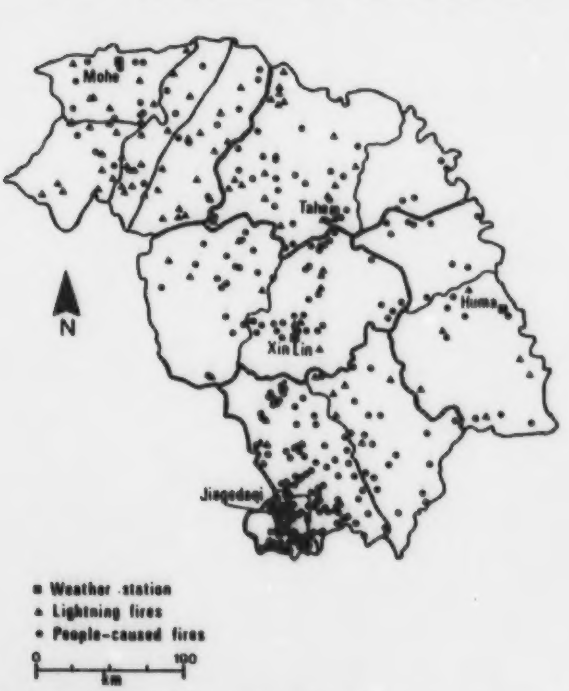


FIG 10. Geographic distribution of the people-caused and lightning-caused forest fires in the Daxinganling Forestry Management Bureau for the period 1975-1984.

Current knowledge of the geographical distribution of lightning activity is sketchy; however, anecdotal evidence confirms that the occurrence of lightning is also common in the southern half of the area. Lightning fires may be more common in the north because the organic layers on the forest floor and the standing larch forest provide a fuel complex that can harbor smoldering fires. Given the right weather conditions, these fires can burn readily. In contrast, the grassy scrublands of the south have very little organic material to support hold-over lightning fires.

A summary of fire occurrence by location, season and cause is presented in Table 2. This table can be used by fire managers to gain an understanding of the seasonal and geographical distribution of the important causes of fires in the DXALFMB. This table was developed through consultation between fire management personnel in the DXALFMB and managers representing the OMNR.

Table 2. Summary of forest fire occurrence in the Daxinganling Forest Management Bureau, by cause, season and geographic location.

	South		North			
Fire Cause	Spring	Fall	Spring	Fall	Month	
Lightning		X	X	X	5,6,7	9,10
Railway		X		X	4,5,6	
Industrial		X		X	3,4,5,6	
Campfires	X	X			3,4,5,6,7	9,10
Pickers					6,7	9,10
Hunters					3,4	9,10
Fishermen					5	10,11
Bee keepers					6,7	9,10
Smoking	X	X	X	X	3,4,5,6,7	9,10

Testing a Daily Forest Fire Occurrence Prediction Model

This section describes a daily people-caused forest fire occurrence model developed by Martell et al. (1987), whose procedure was used to predict the occurrence of people-caused fires in the DXALFMB. Nine years of fire and fire weather data from each sector of the DXALFMB were used to estimate the model parameters. One year of data (1982) was reserved for validating the model. Validation involves comparing the observed fire occurrence with the number of fires predicted by the model.

There are two physical phenomena that influence forest fire occurrence. An ignition source, lightning or the actions of people, is required. As well, there is the condition of the fuel complex as described by its moisture content, type, amount and geometry. The state of the fuel determines the likelihood of a fire, once an ignition (the act of starting a fire), which is distinct from the fire itself (the flaming or glowing combustion of flammable material that will spread if left unattended), occurs.

The model developed by Martell et al. (1987) was based on the assumption that with relatively stable land-use patterns and vegetation conditions, fire occurrence is largely influenced by daily variation in fuel moisture content. Historical weather and fire data showed that the probability (P) of a fire day is an S-shaped function of the FFMC. The following logistic function was used to describe this relationship between P and FFMC:

$$P_{est} = \frac{\exp(b_0 + b_1\ \mathrm{FFMC})}{1+\exp(b_0 + b_1\ \mathrm{FFMC})} \qquad (1)$$

Cunningham and Martell (1973) recognized that the number of fires that occur on a day cannot be predicted exactly and demonstrated that daily people-caused fire occurrence in Ontario exhibited a Poisson distribution. The Poisson distribution can be used to predict the probability of a given number of fires on a specific day:

$$P(x) = \frac{\lambda^x e^{-\lambda}}{x!}$$

where: $P(x)$ = probability that x fires will occur
and λ = expected number of fires per day
The probability that one or more fires will occur is:

$$P[x \geq 1] = 1 - e^{-\lambda} \qquad (3)$$

The probability that one or more fires will occur can be estimated from the logistic regression equation. Solving for λ gives:

$$\lambda_{est} = -\ln(1-P_{est}) \qquad (4)$$

Hence it is possible to estimate the expected number of fires per day.

Logistic regressions were completed for each sector in the DXALFMB in order to estimate the probability of a fire day (P_{est}) for each day in 1982. The P_{est} values were then used to estimate the expected number of fires per day (λ_{est}) for each day, in each season. The sum of the λ_{est} values was calculated for each sector to obtain the expected number of fires per season. This number was compared with the observed number of fires per season to validate the model.

The estimates of the coefficients from the logistic regressions are presented in Table 3 along with the observed and predicted number of fires for each sector (by season). Although the λ_{est} values have been summed for each season in order to get a measure of model performance over the course of a year, the λ_{est} value is the expected number of fires per day. Fire managers can use this to plan daily fire management needs.

Table 3. Logistic regression models of fire occurrence prediction for the Daxinganling Forestry Management Bureau.

Weather Sector	Season	Estimate of model parameter b_0	Estimate of model parameter b_1	Observed no. of fires (1982)	Predicted no. of fires (1982)
Huma	Spring	-18.56310	0.16154	4	3.06
Huma	Fall*	-25.08144	0.23271	0	0.17
Jiagedaqi	Spring	-16.83257	0.16727	32	45.98
Jiagedaqi	Fall	- 5.16087	0.92807	1	4.99
Mohe	Spring	-14.73011	0.12273	4	4.17
Mohe	Fall*	-50.89631	0.52728	0	8.04
Tahe	Spring	-17.40459	0.16060	5	8.04
Tahe	Fall	-26.69514	0.26045	0	0.27
Xin Lin	Spring	-13.37566	9.11540	15	8.57
Xin Lin	Fall*	-32.69867	0.32402	0	0.16

*Because of the lack of fires that occurs in these sectors during the fall, the estimates of parameters b_0 and b_1 are not reliable.

The Great China Fire of 1987

On 6 May 1987, four fires caused by smoking materials and brush-cutting machines broke out in the northwestern portion of the DXALFMB, near the towns of Xi Lin Ji, Mohe, and Amur. Despite the extreme fire danger conditions prevailing, one of these fires was suppressed by early on the morning of 7 May. However, the remaining three fires were well established by this time and, under the influence of strong, gusting winds, each fire spread eastward by between 65 and 80 km by midnight (Fig. 11). Over the next 3-4 weeks, as a result of continued severe fire danger conditions and widespread burnout operations, these fires coalesced to produce one 1,331,000 ha fire in which 191 lives, 56,000 homes, and an estimated 38 million m³ of lumber were lost. More than 40,000 firefighters were mobilized to fight this fire.

Snowfall in the northern portion of the DXALFMB was typically light in the winter of 1986-1987, and the snow had disappeared by early April. Very cool temperatures and low relative humidities prevailed throughout the month of April, when only 7.8 mm of precipitation was recorded at Amur. The first five days of May were also cool and dry, with no precipitation and strong winds. On 6 May the DXALFMB area was under the influence of a ridge of high pressure in the upper atmosphere. Temperatures had risen to near 20°C and relative humidities were down to 5% in the Amur area. The four fires discovered during the day were creating control problems. By 1400 hr on 7 May, the high-pressure ridge over the DXALFMB was breaking down rapidly as a dry cold front approached the region from the west, accompanied by strong, gusting winds. At 1400 hr, Amur recorded a temperature of 22.7°C, a relative humidity of 5%, and a wind speed of 22 km/hr from the west-southwest. The three major fires, not yet contained, moved eastward at extremely high rates of spread as the cold front passed on the evening of 7 May, and winds remained strong and relative humidities low. By early afternoon 8 May, the area was in the warm sector of a surface low pressure

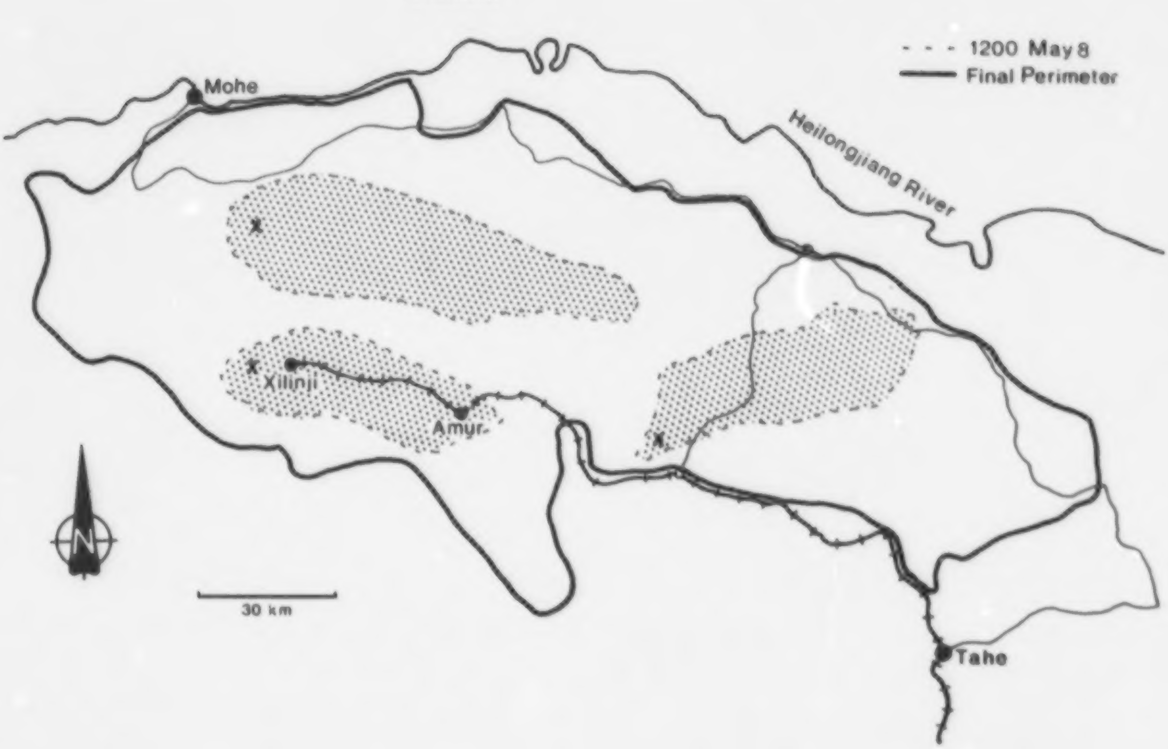


FIG 11. The May 1987 China fire, showing fire origins, perimeters at noon on 8 May, and final perimeters.

system approaching from the west. At 1400 hr, the temperature at Amur was 18°C, the relative humidity was 16%, and the wind speed was 22 km/h from the north-northwest. Despite suppression activities, the three fires spread actively southeastwards on 8 May, although at a much slower rate than on the previous day. Early in the morning of 9 May, the trailing cold front associated with this second low-pressure system passed through the fire area; it brought only light rain but lowered temperatures dramatically for the next week. Suppression activity was reasonably effective during this period as the three fires joined together. Despite periodic flareups throughout the remainder of May, the fire was eventually brought under control in early June, largely as a result of extensive and effective burnout operations.

Although this fire burned for 27 days and required the largest fire control operation in China's history, it was really the result of one day of phenomenal fire behavior. On 7 May, each fire spread at an average rate of 8-10 km/h throughout the afternoon and evening burning period, and covered an area in excess of 350,000 ha in all. This was documented with satellite photography and corroborated by Chinese fire control personnel on-site. By midnight on 7 May, suppression had become a long and difficult process.

Fire weather data for the months of April and May were used to calculate the component codes and indices of the FWI System for a number of stations in the northern DXALFMB. Results were very similar for all stations, and the data for Amur are summarized in Table 4. The results of the calculations shown in in this table are based on weather observations at 1100 hr LST, except in the case of 7 May, when 2200 hr LST readings were used in order to reflect the greatly increased wind speed associated with the passage of the dry cold front through the area during the early evening. The severity of the fire weather during the April-May period in general, and the 6-7 May period in particular, is readily apparent from Table 4. FFMC values greater than 98, ISI levels greater than 50, and FWI values above 50 are strong indicators of explosive, uncontrollable fire behavior. Fires that started late in the afternoon on 6 May easily became well established, and by early on 7 May three fires had already grown to cover several thousand hectares. Strong winds and very low relative humidities throughout the afternoon and evening of 7 May caused each of these fires to grow to more than 100,000 ha before nightfall.

Table 4. Canadian Forest Fire Weather Index System components for the April-May 1987 period for the Amur weather station in the Daxinganling Forestry Management Bureau, China (calculated at 1100hr LST, except for 7 May, which was calculated at 2200 hr.)

Month	Day	Temp. (°C)	Rel. hum. (%)	Wind dir. (deg.)	Wind speed (km/hr)	Precip. (mm)			FWI System component[a]			
							FFMC	DMC	DC	ISI	BUI	FWI
Apr	1	-1.7	4	340	17.0	0.0	85.3	6.0	15.8	5.2	6.2	4.4
Apr	2	1.3	33	340	6.0	0.0	86.4	6.4	16.9	3.5	6.6	2.9
Apr	3	2.8	28	0	0.0	0.0	87.4	7.1	18.4	3.0	7.2	2.5
Apr	4	9.4	15	0	0.0	0.0	90.5	9.2	21.1	4.6	9.2	4.7
Apr	5	10.5	41	180	14.0	0.0	89.5	10.9	23.9	8.1	10.8	8.8
Apr	6	0.6	94	320	1.0	0.1	82.2	10.9	25.0	1.5	10.9	1.0
Apr	7	-5.5	36	320	1.0	3.5	51.8	7.2	22.3	0.2	8.0	0.1
Apr	8	-5.3	29	340	22.0	0.0	68.4	7.2	23.1	1.8	8.1	1.0
Apr	9	-4.6	43	340	26.0	0.4	76.6	7.2	23.8	3.1	8.2	2.9
Apr	10	-5.8	37	360	14.0	0.0	80.8	7.2	24.6	2.5	8.3	2.1
Apr	11	-7.9	31	360	24.0	0.1	83.6	7.2	25.3	5.9	8.4	5.8
Apr	12	2.8	27	340	10.0	0.0	86.7	7.9	26.8	4.4	9.1	4.6
Apr	13	8.0	24	20	15.0	0.0	89.3	9.6	29.2	8.2	10.5	8.8
Apr	14	13.6	18	360	11.0	0.0	92.0	12.5	32.6	9.9	12.8	11.3
Apr	15	9.5	42	0	0.0	0.0	90.7	14.0	34.2	4.7	14.0	6.2
Apr	16	3.2	26	340	19.0	0.0	90.7	14.8	36.8	12.3	14.8	14.3
Apr	17	6.5	16	360	20.0	0.0	91.9	16.3	38.9	15.4	16.3	17.7
Apr	18	7.7	20	360	18.0	0.0	91.9	18.0	41.2	14.0	18.0	17.2
Apr	19	0.6	31	320	7.0	0.0	90.8	18.3	42.3	6.9	18.3	9.9
Apr	20	-1.4	30	50	1.0	1.9	71.1	16.3	43.1	0.7	16.8	0.6
Apr	21	-6.2	42	360	14.0	0.0	77.1	16.3	43.8	1.8	16.9	2.3
Apr	22	-6.8	17	20	17.0	0.0	83.5	16.3	44.6	4.1	17.0	6.0
Apr	23	-0.5	16	360	31.0	0.0	88.5	16.4	45.4	16.5	17.3	19.1
Apr	24	4.4	14	50	11.0	0.0	91.2	17.6	47.2	8.8	18.2	12.2
Apr	25	9.1	11	320	6.0	0.0	93.3	19.8	49.8	9.3	19.9	13.2
Apr	26	6.1	40	200	12.0	1.8	77.3	19.1	51.8	1.6	19.9	2.4
Apr	27	9.8	29	320	6.0	0.0	85.1	21.0	54.5	2.9	21.4	4.9
Apr	28	8.0	53	230	11.0	0.0	85.1	22.0	56.9	3.7	22.4	6.5
Apr	29	4.2	39	110	14.0	0.0	86.1	22.8	58.6	5.0	23.1	8.6
Apr	30	0.8	28	20	28.0	0.0	87.6	23.2	59.7	12.5	23.5	18.0
May	1	3.8	27	360	18.0	0.0	88.6	24.1	62.8	8.7	24.6	14.0
May	2	2.3	28	360	17.0	0.1	88.7	24.7	65.6	8.3	25.5	13.8
May	3	2.5	17	360	25.0	0.0	90.6	25.5	68.5	16.4	26.4	23.1
May	4	10.3	31	20	14.0	0.0	90.6	27.6	72.8	9.5	28.3	16.0
May	5	17.1	8	20	23.0	0.0	95.6	32.0	78.2	29.8	23.0	37.9
May	6	21.6	4	320	23.0	0.0	98.2	37.8	84.5	42.3	37.7	50.8
May	7	14.5	25	90	36.0	0.0	95.2	41.4	90.1	54.8	41.3	62.0
May	8	2.0	88	320	8.0	0.0	85.9	43.8	93.8	3.6	43.7	9.3
May	9	4.7	29	360	14.0	2.6	71.0	37.4	97.0	1.3	38.1	3.1
May	10	6.6	9	320	17.0	0.0	86.8	39.3	100.6	6.4	39.8	14.2
May	11	1.9	34	360	17.0	0.8	84.2	39.8	103.4	4.5	40.6	10.7
May	12	4.8	18	350	23.0	0.0	89.2	41.1	106.6	12.2	41.8	23.4
May	13	6.5	28	360	10.0	0.0	89.3	42.5	110.2	6.4	43.3	14.9
May	14	4.8	48	140	11.0	0.0	87.9	43.3	113.5	5.5	44.3	13.4
May	15	8.5	17	360	1.0	0.0	90.5	45.4	117.4	4.8	46.2	12.3
May	16	13.1	16	20	8.0	0.0	92.6	48.6	122.2	9.3	48.7	20.8
May	17	15.8	12	140	8.0	0.0	94.4	52.5	127.4	11.9	52.4	25.8
May	18	11.6	43	180	14.0	0.0	90.7	54.4	131.9	9.6	54.4	22.5
May	19	5.7	31	360	10.0	0.0	90.4	55.6	135.4	7.5	55.6	19.0

cont'd...

Table 4. Canadian Forest Fire Weather Index System components for the April-May 1987 period for the Amur weather station in the Daxinganling Forestry Management Bureau, China (calculated at 1100 hr LST, except for 7 May, which was calculated at 2200 hr.)

Month	Day	Temp. (°C)	Rel. hum. (%)	Wind dir. (deg.)	Wind speed (km/hr)	Precip. (mm)	FWI System component[a]					
							FFMC	DMC	DC	ISI	BUI	FWI
May	20	6.9	40	20	7.0	0.6	87.8	56.9	139.0	4.4	56.9	13.0
May	21	16.9	8	320	29.0	0.0	95.2	61.2	144.4	38.4	61.2	59.2
May	22	21.9	10	20	7.0	0.0	96.2	66.7	150.8	14.5	66.6	33.1
May	23	8.3	20	230	11.0	0.0	94.7	68.7	154.7	14.5	68.6	33.5
May	24	7.4	83	90	18.0	5.3	49.0	44.2	149.5	0.4	50.8	0.6
May	25	9.3	60	360	7.0	2.5	53.2	38.3	153.5	0.3	47.1	0.5
May	26	2.7	37	250	13.0	0.0	70.8	38.9	156.4	1.2	48.0	3.5
May	27	14.2	41	250	18.0	0.0	83.4	41.3	161.4	4.2	50.3	11.6
May	28	8.5	24	270	42.0	0.2	89.0	43.2	165.3	30.7	52.2	48.0
May	29	22.4	25	250	25.0	0.0	92.2	47.8	171.8	20.7	56.4	38.6
May	30	28.5	15	360	12.0	0.0	95.6	54.4	179.3	17.3	61.9	35.9
May	31	29.0	23	230	17.0	0.0	95.6	60.5	186.9	22.0	66.9	43.6

[a] FFMC = Fine Fuel Moisture Code, DMC = Duff Moisture Code, DC = Drought Code, ISI = Initial Spread Index, BUI = Build-up Index, FWI = Fire Weather Index.

Spread rates approaching 10 km/h, averaged over a 4-hr burning period, are quite phenomenal. In comparison, the Canadian Fire Behavior Prediction System, for ISI levels around 50, predicts maximum spread rates for conifer or 100%-cured grassland fuel types of 3-4 km/h.

The fact that the Chinese fire spread so quickly in fuels that were primarily needleless larch and grass is difficult to explain from Canadian experience. The discrepancy may have been the result of a couple of factors. Long-range spotting from the burning shrubs and needleless larch fuels may have increased the effective rate of spread. The breakdown of an upper-ridge high-pressure system, which often leads to erratic fire behavior (Nimchuk 1983), occurred over the fire zone on 7 May. The CFFDRS (Anon. 1987) does not yet account for the influence of these two factors in estimating rate of spread.

Summary and Conclusions

The CFFDRS can be used to quantify fire weather and fire danger in the DXALFMB, an area of China that is known to have very severe fire danger. The coniferous forests of the northern half of the area are similar to those of the Canadian boreal forest. The DXALFMB has extensive grass and shrub fuel types in the southern half of the area that also make the CFFDRS suitable for use in the area. Fire occurrence prediction, on the basis of the components of the CFFDRS, shows promise for use in the DXALFMB.

The spring period in the DXALFMB is cool, but very windy and dry, with very little precipitation and extremely low humidity levels. This is followed by a wet, warm summer period and a dry cool fall. The result of this consistent annual weather pattern, and the fuel conditions that result, is a distinctly bimodal fire season in which spring fires are numerous and large, fall fires are a lesser problem, and summer fires are virtually nonexistent.

Short-term fire weather, as reflected by the FFMC ISI and FWI components of the FWI System, is very severe throughout the DXALFMB. This is particularly true during the spring period.

Fires in the DXALFMB are very large. This is primarily because of the combination of extreme fire weather and cured grass fuels during the spring period, but may also be a reflection of inadequate detection and initial attack capabilities.

Given the extreme spring fire weather and the extensive grassland fuels in the DXALFMB, large fires will continue to occur regularly, even with improved detection and initial attack capabilities. Adequate protection for the complete areas seems unrealistic, particularly in the southern areas, where grass fuels, predominate.

The fire occurrence prediction equations presented in this paper are part of a people-caused fire occurrence model and should not be used for predicting the occurrence of lightning fires. The model has only been tested in Ontario and should be monitored closely if used in China. If significant changes were to occur in the number of reported fires because of changes in the fire reporting system then the model parameters would have to be re-estimated.

Although the majority of recent large fires within the DXALFMB have occurred in the southern portion of the region, where grass fuels predominate and larch forests have virtually been wiped out, the May 1987 fire illustrates very vividly that large fires can and will happen in the valuable forest in the northern part of this area. Severe annual spring fire weather will continue to present insurmountable problems in this regard. Both Canada and the United States are assisting the Chinese in upgrading their fire management capability in this region, but it is difficult to be optimistic about the future. Implementation of improved prevention, detection, and communication capabilities, and the use of the CFFDRS in presuppression planning, will result in tangible progress. However, much remains to be done if the present and future forests of the DXALFMB are to be adequately protected.

Acknowledgments

We wish to express sincere appreciation to D.L. Martell, Associate Professor, Faculty of Forestry, University of Toronto, for his assistance in using his daily people-caused fire occurrence model in this study.

Special thanks go out to R.A. White and G.E. Xuelin for their cooperation in compiling the data on fire occurrence by cause, location, and season presented in Table 2.

References

ANONYMOUS 1981. Climatic atlas of Asia - volume 1 - maps of mean temperature and precipitation. Prepared by the Voeikov Main Geographical Observatory, Lenningrad, U.S.S.R. World Meteorol. Organ., UNESCO and Goscomgidromet. English, French and Russian. 27 map sheets.

ANONYMOUS 1982a. Canadian climate normals - volume 2 - temperature 1951-1980. Environment Canada, Atmos. Environ. Serv., Downsview, Ont. 306 p.

ANONYMOUS 1982b. Canadian climate normals - volume 3 - precipitation 1951-1980. Environment Canada, Atmos. Environ. Serv., Downsview, Ont. 602 p.

ANONYMOUS 1984. Tables for the Canadian Forest Fire Weather Index System. 4th ed. Dep. Environ., Can. For. Serv., Ottawa, Ont. For. Tech. Rep. 25.

ANONYMOUS 1987. Canadian Forest Fire Danger Rating system -- Users' Guide. Can. For. Serv., Fire Danger Group, Unnumbered Publ.

CUNNINGHAM, A.A., and D.L. MARTELL. 1973. A stochastic model for the occurrence of man-caused forest fires. Can. J. For. Res. 3:282-287.

MARTELL, D.L., S. OTUKOL and B.J. STOCKS. 1987. A logistic model for predicting daily people-caused forest fire occurrence in Ontario. Can. J. For. Res. 17:394-401.

NIMCHUK, N. 1983. Wildfire behavior associated with upper ridge breakdown. Alta. Min. Energy and Nat. Resour., For. Serv., Edmonton. ENR Report No. T/50.

Field Evaluation of a Moisture Content Model for Medium-Sized Logging Slash

B.D. LAWSON AND B.C. HAWKES
Forestry Canada
Victoria, British Columbia

Abstract

A moisture content model for medium-sized logging slash was developed by Van Wagner from field data collected in three-year old jack pine slash averaging 4 cm in diameter. Field tests of this model and its tentative adjustments for slash age and diameter range were conducted by the authors in first-year and second-year old white spruce-subalpine fir logging slash of various diameters. Tests of the model and its assumptions were conducted using both in-situ, roundwood slash samples exposed for the season in trays and weighed daily, and destructive samples stratified by depth increment, taken on a weekly basis. Correlation of this independent data set with Van Wagner's model predictions is presented, along with some possible modifications for these species and age differences and size range from two to ten cm.

The objective of this slash moisture modeling research is to further develop the Canadian Forest Fire Danger Rating System as an aid to quantifying fire danger and behavior in forest cutovers. Eventual use of slash moisture models in prescribed fire decision-aids to improve predictions of slash fuel consumption in silvicultural prescribed burns is discussed.

Résumé

Van Wagner a élaboré un modèle de teneur en humidité des résidus d'exploitation de grosseur moyenne à partir de données recueillies dans des parterres de coupe jonchés de rémanents de pin gris de 3 ans d'un diamètre moyen de 4 cm. Les auteurs ont procédé à des essais au champ de ce modèle et tenté de l'ajuster en fonction de la gamme d'âges et de diamètres des rémanents dans un parterre de coupe à résidus d'épinette blanche-de sapin subalpin de l'année en cours et d'un an à diamètre variable. Le modèle et ses hypothèses ont été vérifiés à l'aide d'échantillons de bois ronds rémanents se trouvant sur le terrain et placés dans des plateaux à l'air libre pendant toute une saison et pesés quotidiennement et à l'aide d'échantillons en décomposition stratifiés selon l'accroissement en profondeur mesuré à chaque semaine. Les auteurs présentent une corrélation entre cet ensemble de données indépendantes et les prévisions du modèle de Van Wagner ainsi que certaines modifications possibles à apporter selon les espèces et les différences d'âge et une gamme de dimensions allant de 2 à 10 cm.

L'objectif de ces recherches sur la modélisation de la teneur en humidité des résidus d'exploitation est d'améliorer la Méthode canadienne d'évaluation des dangers d'incendie de forêt pour aider à quantifier le danger et le comportement du feu dans les parterres de coupe. Les auteurs examinent l'utilisation éventuelle des modèles de teneur en humidité des rémanents par les systèmes d'aide à la décision lors de brûlages dirigés afin de mieux prédire la consumation de combustibles des rémanents lors de brûlages dirigés réalisés à des fins d'aménagement sylvicole.

Introduction

At present, the two main subsystems of the Canadian Forest Fire Danger Rating System (CFFDRS), the Fire Weather Index (FWI) System and the Fire Behavior Prediction (FBP) System (Stocks et al. 1989), do not contain fuel moisture models for woody components of logging slash.

To address the need for improved measurement of fire danger in forest cutovers, Van Wagner (1987) developed a model to predict moisture content in 4 cm diameter logging slash. Conceptually, the model is a moisture budget driven by standard daily fire weather inputs.

Wetting and drying phases were developed separately from field data collected by Stocks and Walker (1972) in three year old jack pine (Pinus banksiana Lamb.) logging slash in Ontario. Van Wagner (1987) discussed generalizing the model for a range of slash wood ages and sizes, using earlier data from Lawson (1985) for west coast Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) and western red cedar (Thuja plicata Donn) to develop a tentative adjustment for age.

The purpose of this paper is to evaluate the Van Wagner (1987) model using new test data for first-year and second-year white spruce (Picea glauca (Moench) Voss) - subalpine fir (Abies lasiocarpa (Hook.) Nutt) logging slash collected during 1987 and 1988 field seasons near Prince George, British Columbia.

Alternatives to mathematical weather-dependent models for woody fuel moisture monitoring, including

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

direct weighing of B.C. Forest Service fuel moisture sticks[1] and direct readout moisture meters, were also evaluated in this study and are briefly discussed.

Literature Review

Simard et al. (1984) reported fair correlation between certain Canadian and U.S. fuel moisture models and some sizes and conditions of jack pine slash wood. Their regression equations for 5 cm slash with bark included Duff Moisture Code (DMC) and Fine Fuel Moisture Code (FFMC) components of the FWI System and produced R^2 of 0.73 with a standard error of 4.2, a slightly better relationship than was achieved using U.S. round wood moisture models. Van Wagner's (1987) goal was a model developed specifically for medium-sized logging slash, in order to improve prediction accuracy. Sufficient Canadian data was not then available to test it much beyond the data set used to develop the model. An existing data set (Lawson 1985) was available for 1 to 3 cm mixed Douglas-fir and western red cedar slash in its first summer of drying on a coastal British Columbia site. Van Wagner (1987) did a partial test of his proposed slash age correction (reduced rainfall effect for first year and second-year slash) using this data.

Subsequently, Trowbridge and Feller (1988) reported good relationships between fine (less than 1 cm) lodgepole pine (Pinus contorta Dougl.) slash moisture and the FFMC, pointing out the necessity of allowing the slash to cure sufficiently (about 3 snow-free months) after cutting before its moisture content can be predicted adequately by such models as FFMC. They also reported high correlation between B.C. Forest Service fuel moisture stick weights and FFMC as predictors of fine slash moisture.

A study currently in data analysis phase (Péch 1988) will provide additional information on continuous wetting and drying over a range of medium slash diameters. This should help resolve some of the problems in using once per day sample weighings to derive daily wetting and drying rates, which hindered both Van Wagner's model development and this present test.

Electric moisture meters of the conductance (resistance) type were thoroughly discussed by James (1988), noting acceptable accuracy is possible at moisture contents less than 30 percent and that readings are affected by such factors as wood species, temperature, moisture distribution and operator skill. Blank et al. (1983) reported field test results of one such meter whose readings were well correlated with observed fuel moisture of 1-inch dead jack pine branchwood.

Methods

Field trials were conducted to evaluate performance of the Van Wagner model in predicting daily moisture content of slash with different species, ages and sizes to those used in its development. Some of the assumptions used in the basic 4 cm slash model and adjustments for other ages and sizes of slash were tested in this new field study, in accordance with Van Wagner's suggestion that, while the basic 4 cm slash model was "moderately sound," his proposed extensions for age and size were "tentative", and required further field testing.

In general, the approach to the model evaluation field trials was similar to that used to gather the original data. White spruce-subalpine fir slash from the March, 1987 clear cutting of a 1960's selectively logged (but poorly regenerated cutover) site near Stony Lake in the Prince George East Forest District of central British Columbia (lat. 53°27'N, long. 121°54'W, elevation 970 m) was selected as the study material. The slash was sampled for moisture content during the 1987 (first year) and 1988 (second year) field seasons. Samples of several diameters of slash of each of the two species were set in galvanized wire-screen trays 30 cm square in an open level area and weighed daily, in the early afternoon. At the end of each season, the tray material was oven-dried and the daily moisture contents calculated. As well, weekly destructive samples of both species for several diameters were stratified by depth specifically to evaluate the "dry centre" assumption used in the model and its extensions. Standard daily fire weather observations (Turner and Lawson 1978) required for calculating the components of the FWI System and the Van Wagner model were recorded at a standard forest fire weather station adjacent to the fuel moisture site. In addition to these noon (local standard time) observations of temperature, relative humidity, 10-minute average wind speed (10 m height) and 24-hour rain, a second station recorded hourly average values of these parameters.

Tray data were collected for white spruce branch and bole wood and subalpine fir branchwood of the same diameter ranges, 2.5 to 5.0 cm, as in the original model; in addition, two fine size classes, 0.1 to 1.0 cm and 1.1 to 2.0 cm, were studied, as were four specific medium diameters, 2.0, 4.0, 6.0, and 10.0 cm. Cut ends and branch cuts of all pieces 2.0 cm and over were double-sealed with melted paraffin at the start of each season. The following characteristics and assumptions in the Van Wagner model were tested across this wide range of fuel size for the two species and ages, separately:

1. Daily drying rate follows a negative exponential model, equation (1), mostly dependent on initial fuel moisture content, and only weakly dependent on daily noon weather variables, temperature (T), relative humidity (H), and wind speed (W).

Van Wagner revised his equation (2) drying rate subsequent to the original published version (Van Wagner 1987); it is reproduced below for current reference:

$$(M - E)/(Mo - E) = e^{-kt} \qquad (1)$$

$$k = 0.023\ e^{0.0182\ T}\ [1-(H/100)^{1.7}](0.1+0.0151\ W^{0.5})\ (Mo-5)^{1.3} \qquad (2)$$

where k is logarithmic daily drying rate,

Mo is initial moisture content (%),
M is final moisture content (%),
E is equilibrium moisture content (EMC)
t is time (days)

The negative exponential drying model (equation 1) was unchanged but evaluated in this study for the suitability of the constant value of 5% for EMC chosen by Van Wagner. Relative contributions of Mo and noon weather measurements to the prediction of observed daily drying rate were evaluated using multiple regression analysis. Correlation of predicted drying rate (xk) from the model and observed drying rate (k) was checked, along with the linearity of the relationship.

2. Daily response to rain, while in reality is a combination of wetting due to rain, followed by subsequent drying after cessation of rain, can be approximated by a model driven by daily rainfall amount and initial fuel moisture content.

This study suffered from the same problem as Van Wagner's in that once-daily measurements of fuel moisture, while taken at approximately the same time each day, represented various combinations of wetting and drying times. This precluded a rigorous analysis of the "gross" rain effect, so only correlations with observed "net" change in moisture content (ΔM) (some negative) could be checked against the net change in moisture following rain plus subsequent drying predicted by the model (cM)[2].

3. Drying and wetting rates for medium-sized slash over a wide range of diameters follow a model suited to "dry-centre" internal distribution of moisture within the piece, such that the outer layer is responsible for most of the wetting and drying response to current weather conditions. The dry-centre mode supports the theory of faster drying rates than would be expected for uniform distribution of moisture with depth, or for "wet-centre" mode.

The destructive sampling of slash of both species for the "dry-centre" evaluation was done on a dry day (no rain in last 24 h) every four or five days. Two samples of each species in three diameters (3, 6 and 10 cm) were cut from branchwood or bole wood of the fully exposed slash used to supply the tray material. Cross-sections were stratified and split by 2 cm depth increments from top to bottom of the piece (1 cm increments for 3 cm diameter samples). Each depth stratum for each sample was separately oven-dried for moisture content determination. The whole data set was analyzed for trends, separately by year, season, species and diameter.

4. An extension of the model to diameters other than the 2.5 to 5.0 cm slash size used in its development has been suggested, based on the assumption that both drying rate and rainfall effect vary with the square root of diameter. The strengths of our observed relationships of drying and wetting rates with slash size were evaluated using log-log slope analysis.

5. Taking 60% and 80% of the total rain effect on daily slash fuel moisture for first and second-year slash respectively had been suggested for trial use as an age adjustment to the basic model developed for three-year old heavily checked slash. This approach had been tentatively supported by Van Wagner's test against an independent data set (Lawson 1985) of cured first-year slash of different species and size. We evaluated the model's rainfall effect with the age adjustments suggested by Van Wagner (1987), over our range in diameters, using regression analysis against our observed rainfall effects on fuel moisture.

6. Moisture content of very fine slash less than about 2 cm diameter can be better predicted by models such as FFMC and fuel moisture sticks, probably because as size decreases, the slash spends more time near its EMC and the internal moisture distribution becomes more uniform. The FFMC particularly, with variable EMC and k that remains constant with M would be expected to be superior to the present model for very fine slash. Regression analysis was used to evaluate the Van Wagner slash model, FFMC and fuel moisture sticks as predictors of moisture content of 0.1 to 1.0 cm and 1.1 to 2 cm subalpine fir slash.

An additional objective of the study, to be briefly discussed, was to investigate the viability of direct fuel moisture content determination using resistance-type meters as an alternative to weather-dependent models for medium slash. While typical performance of these meters has been reported in several earlier studies, an investigation of their usefulness in medium and large slash moisture determination above fibre saturation was undertaken as an adjunct to the present study.

In 1988, a Triton-2000[3] digital wood moisture meter was used in a comparison trial of accuracy against standard oven-drying for fuel moisture determination. The sample material was the 6 and 10 cm spruce and subalpine fir slash sampled approximately weekly for the "dry-centre" assumption test. Each 2 cm-deep increment from each 6 and 10 cm diameter piece was split and read with the moisture meter, using three separate 1 cm insertions and readings of the double-pinned probe into the cross section. Three meter readings were averaged for comparison regressions against oven-dry fuel moisture contents of each piece. No corrections were applied to the meter readings for species or temperature.

Results and Discussion

The regression of predicted daily moisture content vs. observed tray moisture content using Van Wagner's (1987) model suggested adjustments were needed in the model's extension for slash age and diameter for white spruce-subalpine fir slash. Correlation coefficients were poor for first-year slash of the same 2.5 to 5.0 cm sizes used to develop the basic model, but improved for second year slash (highly significant[4] $R^2 = 0.61$ and 0.52 for spruce and subalpine fir respectively, Table 1). Of the first-year slash sizes, only fine slash (0.1 to 1.0 cm) was well correlated with the model ($R^2 = 0.76$), whereas all the medium slash sizes up to 6 cm were highly correlated in the second year (R^2 in the 40's and 50's). Ten cm slash moisture was not correlated with the model either year.

Taking our study objectives in turn:

1. Predicted drying rates (xk) were poorly correlated with observed daily drying rates (k) for all sizes from 2 to 5 cm for first-year slash. R^2 increased to only 0.33 for second-year 4.0 cm subalpine fir slash. Correlations improved somewhat for second-year slash of (>5 cm) larger diameters, with a highly significant R^2 of 0.60 for 10 cm white spruce (Table 1) and linear relationship. One problem with modelling current year slash moisture is that the first season has a combination of "green" and "cured" drying periods with markedly different drying rates.

In this study, first-year slash appeared to cross the transition from green to cured about mid-July, by which time most slash diameters had dried down to fibre saturation (about 30%) or below, in spite of three consecutive days of heavy rain totalling 65 mm between July 6 to 8 (Fig. 1).

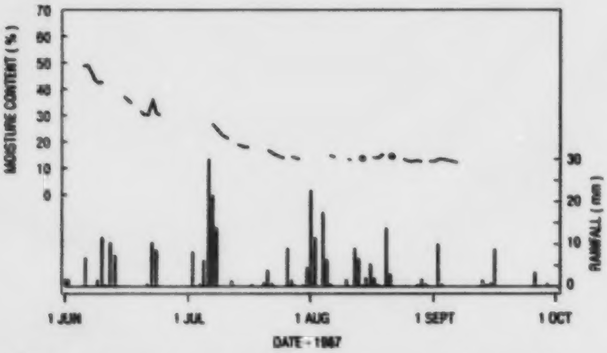


FIG 1. Observed seasonal moisture content change of first-year 2.5 - 5.0 cm white spruce slash in trays with rainfall amount.

The two seasons studied were quite variable in terms of weather conditions and tray fuel moisture which was useful for the model evaluation. Ranges of these variables are given in Table 2 for first-year and second-year slash. The two seasons were similar in that both had maximum consecutive rainless periods of 8 days and maximum consecutive rainy periods of 7 days during the fuel moisture measurements.

Of the three weather variables, only T was correlated to any degree with the observed k, with R^2 in the 0.20's and 0.30's for second-year slash. Combining Mo with the weather variables (T, H and W) produced highly significant R^2 of 0.73 and 0.71 for second-year 0.1 to 1.0 cm and 1.1 to 2.0 cm fine slash, respectively). For the medium slash sizes, the combined variable R^2 remained in the 0.30's and 0.40's.

Table 2. Ranges and means of 1987 and 1988 noon (Pacific Standard Time) weather observations and medium slash fuel moistures of white spruce and subalpine fir samples exposed in trays in the open.

Parameter	First-Year[1] Min	First-Year[1] Max	First-Year[1] Mean	Second-Year[1] Min	Second-Year[1] Max	Second-Year[1] Mean
Temperature (°C)	6.7	28.1	18.3	8.1	26.5	16.8
Relative Humidity (%)	24	86	50	25	83	53
Wind Speed (km/h)	0	26	8.4	1	25	10.2
Rain (mm)	0.3	30	2.9	0.3	19	2.0
Spruce 2-5 cm (%)	12	49	21	17	40	29
Subalpine fir 2-5 cm (%)	14	42	22	23	42	32

[1] Statistics for sampling periods only: June 8 - Sept. 7, 1987; May 31 - Sept. 1, 1988.

2. The rainfall phase (cM) was poorly correlated with observed daily rainfall effects (ΔM) for all sizes of first-year slash (R^2 in the 0.30's), but was better in second-year slash, with R^2 generally in the 0.40's and highly significant ($R^2 = 0.70$) for 2 cm subalpine fir. ΔM's were not significantly correlated with rainfall amount for first or second-year medium slash sizes. ΔM's were also not well correlated with Mo (previous day's observed moisture content) for first year slash, and only moderately and negatively correlated with Mo for second-year slash (R^2 in 0.30's). The highest correlations were found for one-year old fine slash in the two smallest diameter ranges with R^2 in the 0.50's.

Again, the problem of slash curing in the current year was partially responsible for the poor relationships found between wetting effects and rainfall amounts. "Green" slash with diameters greater than 1 cm wets and dries somewhat independently of rainfall and daily weather up to the middle of July in the first year; a model of the wetting and drying process would appear to be of little utility until the slash material reaches the "cured" stage and is more responsive to a changing weather environment.

As found by Van Wagner (1987), this study indicated that most small rains (up to 2 mm) produced negative ΔM's on a "net" basis. Overall the rainfall effect in Van Wagner's model was judged to be too large, especially as diameter increased, although a plot of cM vs ΔM was linear.

Multiple regressions of ΔM vs. Mo, rainfall duration and total daylight hours since rain stopped showed that except for the finest size slash, total daylight hours was the strongest variable (combined R^2 from 0.29 to 0.82). Substituting for rain duration other "time since rain stopped" variables, i.e., total hours and total drying hours since rain stopped, improved R^2 to the 0.70's and 0.80's, with Mo and total daylight hours the most significant variables. The exception was the finest size slash, in which a highly significant R^2 of 0.86 with rainfall duration, dropped to 0.68 without it. For prediction of medium slash rainfall effect, time since

Table 1

Linear regression statistics of slash model outputs (Van Wagner 1987) against observed first- and second-year slash samples exposed in trays in the open, by species and diameter

Model feature	Species	Diam. (cm)	First-year slash Days (n)	First-year slash Y-intercept	First-year slash Slope	First-year slash R^2	First-year slash RMSE[7]	Second-year slash Days (n)	Second-year slash Y-intercept	Second-year slash Slope	Second-year slash R^2	Second-year slash RMSE
xM[1]	B[4]	0.1-1	52	7.1	0.12	0.23	2.6				NS	
	B	1.1-2	52	4.9	0.52	0.35*	4.7	52	-0.93	0.66	0.76*[6]	3.1
	S[5]	2	52	11	0.29	0.20	5.4	52	-3.9	0.52	0.48*	4.7
	B	2	52	5.5	0.52	0.23	5.2	52	-3.7	0.50	0.59*	4.1
	S	2.5-5				NS[8]		52	-5.9	0.91	0.61*	3.9
	B	2.5-5				NS		52	-14	1.1	0.53*	4.3
	S	4				ND[9]		52	-8.9	1.1	0.56*	4.0
	B	4				ND		52	-6.9	0.83	0.53*	4.2
	S	6				NS		52	-7.7	1.1	0.50*	4.0
	B	6				NS		51	-28	1.4	0.47*	4.1
	S	10	52	10	0.34	0.16	4.6	51	3.1	0.82	0.25	4.4
	B	10	52	11	0.29	0.13	4.7				NS	
xk[2]	B	0.1-1				NS					NS	
	B	1.1-2				NS		21	0.03	0.51	0.48	0.04
	S	2				NS					NS	
	B	2				NS					NS	
	S	2.5-5				NS					NS	
	B	2.5-5				NS					NS	
	S	4				ND		21	0.04	0.67	0.33	0.03
	B	4				ND		21	0.04	0.56	0.34	0.03
	S	6				NS		21	0.04	0.53	0.34	0.02
	B	6				NS		19	0.03	1.2	0.44	0.02
	S	10				NS		21	0.03	0.89	0.60*	0.01
	B	10				NS		19	0.04	0.92	0.40	0.02
cM[3]	B	0.1-1				NS					NS	
	B	1.1-2				NS					NS	
	S	2				NS		19	10	1.3	0.54	5.7
	B	2				NS		19	9.4	1.2	0.71*	4.6
	S	2.5-5				NS		19	7.2	1.4	0.56	4.2
	B	2.5-5				NS		19	7.9	1.4	0.39	4.8
	S	4				ND					NS	
	B	4				ND		19	6.6	1.2	0.47	4.0
	S	6				NS					NS	
	B	6				NS		19	5.5	1.7	0.42	3.5
	S	10				NS					NS	
	B	10				NS					NS	

---

[1] Predicted moisture content
[2] Log. drying rate
[3] Net ΔM after rain
[4] subalpine fir
[5] white spruce
[6] * denotes significant at 0.0001 level; all others significant at 0.01 level or better.
[7] root mean square error
[8] not significant at 0.01 level or better
[9] no data

rain stopped was such a significant variable that it would be difficult to operate a once-a-day scheme that cannot apportion between drying and wetting hours. The advent of hourly fire weather data recording systems now makes more complex fuel moisture models, like Van Wagner's (1977) hourly version of FFMC operationally feasible.

3. Van Wagner's "dry-centre" assumption of internal moisture distribution[5] to support daily drying rates higher than would be expected for uniform or "wet-centre" distribution was not found to be consistent by the current study results of the proportional frequencies and persistence of the dry-centre pattern by species, diameter and season (Table 3). Only 3 cm subalpine fir followed dry-centre throughout the current year, but the trend did not persist beyond mid-July of the second year. Ten cm subalpine fir did not follow dry-centre mode in either year, while 6 cm fir followed the pattern only in the first spring. Only 3 cm spruce (although samples were not available for last half of the second year) exhibited the dry-centre pattern in the first spring.

Persistence of the dry-centre assumption results indicated that only diameters < 6 cm in both species showed consistent trends, with a maximum of 7 days for the longest streak (3 cm first-year subalpine fir).

4. Van Wagner's proposed extensions of his 4 cm diameter model to other diameters are based on his tentative conclusion with partial support from other studies, that both drying rate and rainfall effect decreased with the square root of diameter up to 10 cm. He contrasted his findings with those of Nelson (1969), for wet-centre drying and the U.S. fuel moisture models (Bradshaw and Deeming 1983), whose timelags varied as the square of diameter.

In this study, slope of logarithmic drying rate (k) vs. logarithm of diameter varied from -0.61 to -0.87 (Table 4), depending on species and age of slash, supporting a stronger decrease in drying rate with increasing diameter than assumed in the Van Wagner model, although it is a much gentler slope than indicated in the U.S. references.

We found also that rainfall effect decreased with increasing diameter much more steeply than Van Wagner's slope of -0.5. Our log-log slopes ranged from -1.22 to -1.36 (Table 4), depending on species and age, more consistent with Van Wagner's (1987) concept that rainfall effect, if moisture were distributed evenly throughout the piece, should be proportional to the surface-to-volume ratio of the piece (2/radius). Van Wagner accounted for his gentler slope with diameter

Table 3

Proportional frequencies and persistence of the "dry-centre" assumption in destructively sampled slash by species, diameter, and season.

Sample Year	Slash Species	Slash Diameter (cm)	Proportional Frequencies[1] Season Spring[2] (%)	Spring[2] Total Sample Days	Summer[3] (%)	Summer[3] Total Sample Days	Total (%)	Total Total Sample Days	Persistence of Trend No. of Streaks[4]	Longest Streak[5] (days)
1	B[6]	3	83	12	68	19	74	31	2	7
1	B	6	83	12	41	17	59	29	2	5
1	B	10	0	11	7	14	4	25	0	0
1	S[7]	3	46	11	29	21	34	32	2	5
1	S	6	20	10	11	19	14	29	0	0
1	S	10	30	10	13	16	19	26	0	0
2	B	3	70	10	29	14	46	24	2	5
2	B	6	20	10	43	14	33	24	1	4
2	B	10	0	10	0	14	0	24	0	0
2	S	3	40	10	ND[8]		ND		0	0
2	S	6	0	10	ND		ND		0	0
2	S	10	0	10	ND		ND		0	0

---

[1] Proportion of total sample days which exhibited the dry-centre pattern $\left(\frac{\text{no. of days with dry-centre}}{\text{Total no. of sample days}} \times 100.\right)$

[2] Defined here as the period from the start of fuel moisture sampling to July 15.

[3] Defined here as the period from July 16 to the end of fuel moisture sampling.

[4] A streak is a period of three or more consecutive days exhibiting the dry-centre pattern.

[5] The maximum number of days in any one streak.

[6] Subalpine fir.

[7] White spruce.

[8] ND - no data.

Table 4. Logarithmic slopes of observed drying rates (k) and net rainfall effects (ΔM) against log. diameter by species and age of slash.

Species	Year	Slope	R^2	Diam. range (cm)	No. Trays (n)
1. log. drying rate (k) vs. log. diameter					
B	1	-0.61	0.95	0.3-10	6
B	2	-0.79	0.93	0.3-10	11
S	1	-0.87	0.98	2.0-10	4
S	2	-0.82	0.77	2.0-10	9
2. log. net rainfall effect (ΔM) vs. log. diamter					
B	1	-1.22	0.87	0.3-3.3	4
B	2	-1.23	0.28	2.0-6	6
S	1	insufficient data[1]			
S	2	-1.36	0.42	2.0-10	8

[1] Only two trays had positive mean ΔM, precluding analysis of log. slope; only trays with positive mean ΔM are included in this analysis.

by his assumption of dry-centre moisture distribution.

5. The simple 60% proportion of total rainfall effect suggested by Van Wagner as a tentative adjustment for first-year slash was derived from a study of first-year Douglas-fir and western red cedar slash in coastal British Columbia (Lawson 1985). Van Wagner obtained a slightly better fit and R^2 (0.75 vs 0.70) for predicted vs. observed fuel moisture for this data set of 1 to 3 cm mixed species slash using 60% of the rainfall effect (Fig. 2). It should be noted that the coastal B.C. data was for the first season only, and began in late July, after the winter-logged slash had already cured below fibre saturation.

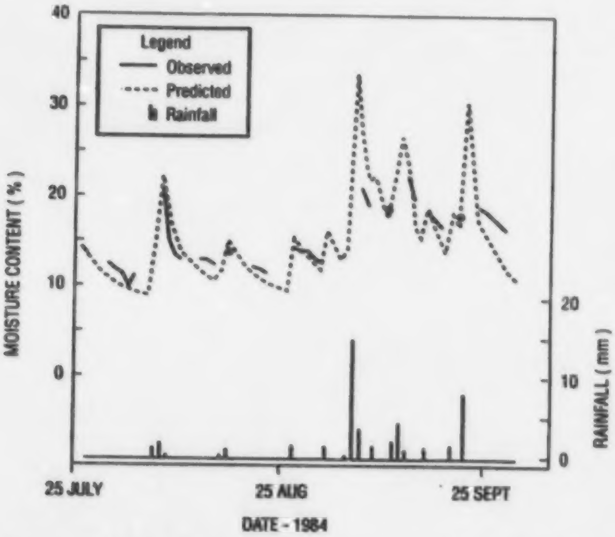


FIG 2. Predicted (Van Wagner (1987) model) compared to observed moisture content of first-year 1-3 cm Douglas-fir/western red cedar slash in trays near Shawnigan Lake, B.C., with rainfall amount.

Testing the proposed age adjustment in the present study was complicated by the "green" stage of first-year slash so a subset of the first-year data was evaluated, beginning July 10, 1987 after three consecutive days of heavy rains totalling 65 mm. Slash moistures had dropped to fibre saturation within a day or two of these rains, suggesting that a more realistic evaluation of the age adjustment than provided by the whole season might be possible using the second half-season data only. However, having determined that the model rainfall effect was too large for both ages and all diameters tested, we could not extend correlation analysis for the first-year slash because of insufficient data in that year's cured period. The second-year rainfall effect, a proposed 20% reduction from the third-year model standard value, was too large for the 2 to 5 cm diameters used in the basic model and much too large for the 6 and 10 cm sizes. Therefore, we decided to re-evaluate the rainfall effect independently of slash age, in combination with diameter, as discussed later with our other proposed model changes.

6. Our results agreed with Van Wagner (1987) with regard to the superiority of FFMC for predicting moisture content of very fine slash. Subalpine fir slash 0.1 to 1.0 cm was significantly correlated with FFMC in both years (R^2 = 0.69 and 0.87, respectively) whereas the slash model was not. However, the slash model performed better than FFMC for the 1.1 to 2.0 cm slash in both years, with a highly significant R^2 of 0.76 for the second year, as against 0.67 for FFMC.

Fuel moisture sticks were about as well correlated with fine slash moisture (0.1 to 1.0 cm) as FFMC for both years for all days (R^2 = 0.81 vs 0.69 and 0.82 vs. 0.87 for first-year and second-year respectively). However, for the more critical drier days, FFMC above 79, FFMC performed slightly better than fuel moisture sticks (R^2 = 0.87 vs 0.68).

These results, coupled with the good correlation between the slash model and the coastal B.C. first-year (cured) slash of 1 to 3 cm suggests that Van Wagner's explanation is probably correct, that as size decreases below 2 cm, the slash spends more time near its EMC and, also, its internal moisture distribution becomes more uniform. The problem, then, is to calibrate the various features of the model, i.e., EMC, effect of diameter on drying and wetting, and overall magnitude of the rainfall effect to produce more useful results over the range of diameters up to 10 cm.

The above results from testing the assumptions in the Van Wagner model suggested several changes to the model that could improve its applicability to our study's data (Fig. 3). Four changes were tried as follows:

1. Raising EMC from 5 to 9%, to better reflect observed ranges of minimum moistures of cured medium-sized slash from destructive sampling and tray measurements. The wax-sealed ends of the tray-sample pieces and the generally sound bark during the first

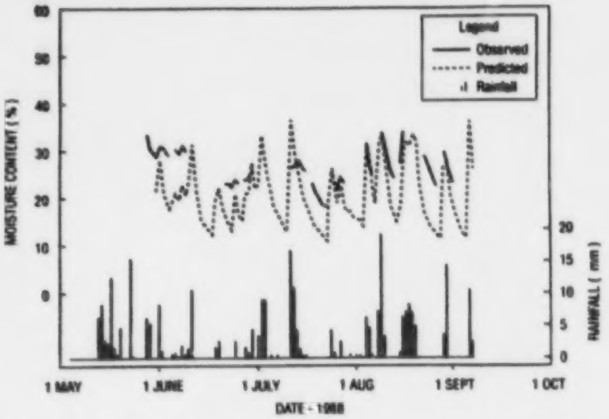


FIG 3. Predicted (Van Wagner (1987) model) compared to observed moisture content of second-year 4 cm white spruce slash in trays at Stony Lake, B.C. with rainfall amount.

two years appear to keep the EMC's for this material higher than for the original model data set, where ends were not sealed and pronounced cracking of bark had occurred. Van Wagner set the model EMC to 5% for mathematical reasons to ensure a spread of about 4 or 5% remained between EMC and expected field minimum values so that the model would function properly at the dry end (Van Wagner, personal communications, Apr. 6, 1989). Our increase to 9% would retain a similar spread for all but the finest slash sizes.

2. Reducing the rainfall effect with rain amount. A function of the same shape but half the magnitude was selected, following the pattern of the relationships with several of the size classes. Van Wagner's rain function f(R) approaches 1 at rainfall amount R of 30 mm, with larger rains having no further effect on cM and a maximum possible cM by his equation 3 of 57 points when EMC=5. Our reduction of the rainfall effect operates through reducing the f(R) to approach 1 at R of 15 mm, requiring the constant of 45.7 to be reduced to 23.7. This change results in a maximum possible cM of 15 points at our new EMC of 9.

3. Steepening the decline of rainfall effect with increasing diameter, to better reflect the negative slope of this relationship in our data. Van Wagner's slope of -0.5 was increased to -1.2 for trial.

4. Steepening the decline of drying rate with increasing diameter to better reflect the larger negative slope in our data. Van Wagner's square root relationship was increased from 0.5 to the 0.8 power.

Results of these model changes are summarized in Table 5. Overall, the changes significantly improved the R^2 and root mean square errors in regressions of predicted vs. observed fuel moistures for both ages for the 6 and 10 cm diameters, while not adversely affecting the 2.5 to 5 cm standard model size range. However, slopes continued to differ significantly from one, and as shown in Fig. 4, underprediction of the model increased for the standard diameters. No age effect could be resolved between first and second-year slash from the present analysis.

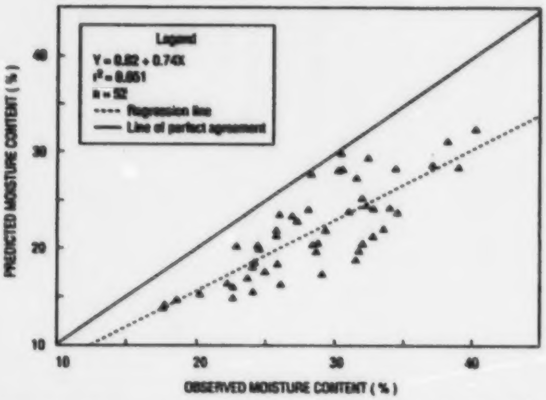


FIG 4. Regression of predicted (modified Van Wagner (1987) model) vs. observed moisture content of second-year 2.5 - 5.0 cm white spruce slash in trays at Stony Lake, B.C. compared to the line of perfect agreement.

It was interesting to compare the best possible correlations between the slash model predictions and daily moisture content of 2.5 to 5 cm slash in trays with correlations between FFMC and DMC, non-roundwood models in the FWI System. R^2 of 0.65 for the former compared with 0.70 from the latter multiple regression, with the same error of 3.0, quite similar to Simard et al.'s (1984) earlier results.

It would appear at this stage that the Van Wagner medium slash model is not as robust, i.e., extendible to slash fuel conditions beyond the data used in its derivation, as the standard fuel moisture codes of the FWI System. Further development and testing of medium slash moisture models using more refined data sets, in terms of the separation of "gross" rainfall effects from "net" combined wetting and subsequent drying, may be warranted. An appropriate age relationship from fresh "green" slash through total bark shedding age remains a need.

Direct measurement of woody fuel moisture can be an attractive option to weather-dependent mathematical models. In this study, the destructive samples taken approximately weekly for the "dry-centre" assumption tests were found to be highly correlated (R^2 = 0.70) between their oven-dry moisture contents and the mean of three separate readings of each piece taken with the Triton-2000 digital wood moisture meter. This regression was restricted to actual fuel moistures below 45%, and it is evident from the scatter plot (Fig. 5) that, as with most studies of these types of meters,

Table 5[1]

Linear regression statistics of outputs from slash model, modified for EMC, rainfall effect with rain amount, and for drying rates and rainfall effect with diameter.

Model feature	Species	Diam. (cm)	First-year slash					Second-year slash				
			Days (n)	Y-intercept	Slope	R^2	RMSE	Days (n)	Y-intercept	Slope	R^2	RMSE
xM	B	0.1-1				NS					NS	
	B	1.1-2	52	8.0	0.46	0.36*	4.1	52	4.0	0.53	0.70*	2.9
	S	2	52	14	0.28	0.20	5.1	52	1.0	0.45	0.48*	4.1
	B	2	52	8.3	0.51	0.25	5.0	52	1.2	0.43	0.58*	3.7
	S	2.5-5				NS		52	0.82	0.74	0.65*	2.9
	B	2.5-5				NS		52	-4.8	0.85	0.53*	3.4
	S	4				ND		52	0.0	0.85	0.57*	2.9
	B	4				ND		52	0.88	0.65	0.57*	3.0
	S	6	52	18	0.14	0.14	3.9	52	2.1	0.78	0.60*	2.3
	B	6				NS		51	-14	1.03	0.55*	2.6
	S	10	52	12	0.35	0.33*	2.9	51	8.1	0.60	.46*	2.0
	B	10	52	12	0.32	0.28*	3.1	51	12	0.33	.21	3.3
xk	B	0.1-1				NS					NS	
	B	1.1-2	24	0.05	0.60	0.26	0.04	21	0.04	0.46	0.47	0.04
	S	2				NS					NS	
	B	2				NS					NS	
	S	2.5-5				NS		13	0.04	0.39	0.31	0.03
	B	2.5-5				NS		21	0.04	0.70	0.36	0.03
	S	4				NS		21	0.03	0.53	0.40	0.02
	B	4				NS		21	0.03	0.44	0.41	0.02
	S	6				NS		21	0.03	0.38	0.48	0.01
	B	6				NS		19	0.03	0.68	0.46	0.01
	S	10				NS		21	0.03	0.30	0.46	0.01
	B	10				NS					NS	
cM	B	0.1-1				NS					NS	
	B	1.1-2				NS					NS	
	S	2	13	11	1.9	.41	9.2	19	9.7	1.1	0.49	5.7
	B	2				NS		19	9.0	1.1	0.67*	4.7
	S	2.5-5				NS		19	5.2	0.85	0.42	3.3
	B	2.5-5				NS					NS	
	S	4				ND					NS	
	B	4				ND					NS	
	S	6				NS					NS	
	B	6				NS					NS	
	S	10				NS					NS	
	B	10				NS					NS	

---

[1] See Table 1 for explanatory notes

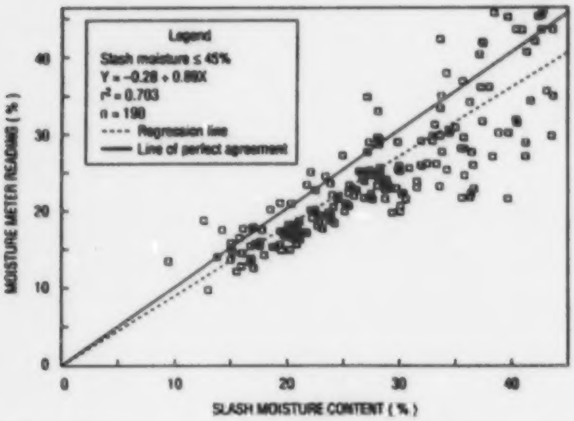


FIG 5. Regression of Triton-2000 moisture meter readings vs. observed 6 and 10 cm white spruce and subalpine fir moisture content compared to the line of perfect agreement.

their accuracy and precision falls off rapidly above fibre saturation, about 30%.

Conclusions

The Van Wagner (1987) medium slash model is highly correlated with the moisture content of white spruce and subalpine fir second-year slash up to 6 cm in diameter. The model is not well correlated with first-year slash moisture or with moisture content of slash as large as 10 cm diameter. This is because, even though the model's rainfall effect is reduced for new and second-year slash and slash of diameters greater than 4 cm, these reductions do not appear to be sufficient. The model ranges considerably above and below observed moisture contents of first- and second-year slash, the low end problem contributed to by a rather low and fixed EMC chosen for the model. Also, the model's "dry-centre" assumption about internal moisture distribution, was not verified consistently for slash larger than 3 cm, resulting in predicted daily drying rates too high for diameters larger than the 4 cm standard. The present analysis of drying rate as affected by current weather was not conclusive, but suggests the possibility of a stronger relationship to temperature than in the model.

Moisture of slash less than 1 cm in diameter is better predicted by FFMC or fuel moisture sticks than the medium slash model, and even medium sized slash (2.5 to 5 cm) is highly correlated with FFMC and DMC. Moisture meters can be used effectively and accurately below 30% to directly measure moisture content of medium-sized slash; however, as with any fuel sampling scheme, obtaining readings representative of the fuel of interest over the cutover area is a problem.

Further study of moisture model improvements for medium-sized slash are probably warranted, as the present model and test procedures and results all have shortcomings. Future work should include the evaluation of potential improvements in prediction of slash fuel consumption using models or measurements of medium-sized slash moisture for prescribed fire decision-aids, before major new work on slash moisture models for the CFFDRS is undertaken. Correlative models using standard moisture codes from the FWI System may be difficult to significantly improve on when prescribed fire behavior and impact prediction is the ultimate fire management objective.

Acknowledgements

The authors would like to acknowledge the following contributors: M. Grismer was responsible for the field data collection with assistance from students C. Doyle (1987) and J.D. Roberts (1988); R. Silversides and R. Benton provided backup weather data at the Stony Lake site. B.C. Forest Service Protection staff at Prince George East District assisted with collecting and archiving the automatic fire weather station data for the study. R. de Jong, B. Armitage and J. Sadr assisted with data analysis. G. Péch provided valuable advice on the experimental design. Partial funding for the study provided by Canada/B.C. Forest Resource Development Agreement, Cost-Shared Project 1.20.

Endnotes

[1] Referred to as fuel moisture sticks in rest of paper. B.C. Forest Service half-inch (1.3 cm) Douglas-fir fuel moisture sticks weighing 100 g oven-dry are currently manufactured to B.C.F.S. standards (Bell 1970) by Dick's Firesticks, Mackenzie, B.C. under the trade name "The Dick Fuel Moisture Stick".

[2] Throughout this paper cM denotes predicted net moisture content change after rainfall plus subsequent drying; ΔM denotes the observed value. Final moisture content predicted for the day is denoted xM, while M denotes the observed value.

[3] Triton moisture meters are manufactured by Valley Products and Design Inc., Milford, Pa.

[4] "highly significant" in this paper denotes significance level of 0.0001.

[5] Defined here as the innermost 1 or 2 cm strata having lower moisture content than the rest of the piece.

References

BELL, P.A. 1970. The production of fuel moisture sticks. B.C. For. Serv., Prot. Div., Victoria, B.C. Planning Res. Rep. 42.

BLANK, R.W., J.D. FROST, AND J.E. EENIGENBURG. 1983. A probe for measuring moisture content in dead roundwood. USDA For. Serv. Res. Note NC-306, North Central For. Exp. Sta.

BRADSHAW, L.D., AND J.E. DEEMING. 1983. The 1978 National Fire-Danger Rating System: technical documentation. USDA For. Serv. Gen. Tech. rep. INT-169, Intermtn. For. and Range Exp. Sta.

JAMES, W.L. 1988. Electric moisture meters for wood. USDA For. Serv. Gen. Tech. Rep. FPL-GTR-6, For. Products Lab, Madison, WI.

LAWSON, B.D. 1985. Current research in B.C. to improve prescribed fire behavior and impact prediction. Paper pres. at Coastal Prescribed Fire Behavior and Use Seminar, Duncan, B.C., Nov. 6-7, 1985, Report on file (PC-63), Forestry Canada, Pacific Forestry Centre, Victoria, B.C.

NELSON, R.M., JR. 1969. Some factors affecting the moisture timelags of woody materials. USDA For. Serv. Res. Pap. SE-44, Southeastern For. Exp. Sta.

PÉCH, G. 1988. Rain and dew on slash-wood, needle litter, and reindeer lichen - experimental procedures. Progress report on file at Forestry Canada, Petawawa National Forestry Institute, Chalk River, Ontario, (File No. 6659-2).

SIMARD, A.J., J.E. EENIGENBURG, AND R.W. BLANK. 1984. Predicting fuel moisture in jack pine slash: a test of two systems. Can. J. For. Res. 14:68-76.

STOCKS, B.J., AND J.D. WALKER. 1972. Fire behavior and fuel consumption in jack pine slash in Ontario. Can. For. Serv. Inf. Rep. 0-X-169, Great Lakes For. Res. Centre, Sault Ste. Marie, Ontario.

STOCKS, B.J., B.D. LAWSON, M.E. ALEXANDER, C.E. VAN WAGNER, R.S. MCALPINE, T.J. LYNHAM AND D.E. DUBÉ. 1989. The Canadian Forest Fire Danger Rating System: an overview. For. Chron. 65(6):450-457.

TROWBRIDGE, R., AND M.C. FELLER. 1988. Relationships between the moisture content of fine woody fuels in lodgepole pine slash and the Fine Fuel Moisture Code of the Canadian Forest Fire Weather Index System. Can. J. For. Res. 18:128-131.

TURNER, J.A., AND B.D. LAWSON. 1978. Weather in the Canadian Forest Fire Danger Rating System: a user guide to national standards and practices. Environ. Can., Can. For. Serv., Inf. Rep. BC-X-177, Pac. For. Res. Cent., Victoria, B.C.

VAN WAGNER, C.E. 1977. A method of computing fine fuel moisture content throughout the diurnal cycle. Fish. Environ. Can., Can. For. Serv. Inf. Rep. PS-X-69, Petawawa For. Exp. Sta., Chalk River, Ontario.

VAN WAGNER, C.E. 1987. A moisture content model for medium-sized logging slash. P. 34-40 In Proc. Ninth Conf. Fire and For. Meteor., San Diego, Calif., Apr. 21-24, 1987, Am. Meteor. Soc., Boston, Mass.

The Influence of Fuel Packing, Moisture, and Inorganic Contents on the Heat Evolved From Smoldering Peat

W.H. FRANDSEN
Intermountain Research Station, Forest Service
U.S. Department of Agriculture
Missoula, Montana

Abstract

Smoldering ground fires, although not as dramatic as surface fires, can raise mineral soil temperatures near the surface above 400°C for several hours with peak temperatures above 600°C. Such temperatures can result in the decomposition of organic material and the death of mineralizing organisms that provide nitrogen in an available form for root uptake. The underlying factor contributing to these temperatures is the heat of combustion released in the smoldering process.

Heats of combustion were investigated at different organic concentrations, and moisture and inorganic contents by monitoring the mass of oxygen consumed during combustion. The smoldering sample was contained in a sealed cylinder. Air was allowed to flow through the cylinder at a rate sufficient to sustain combustion as in the field.

Bulk concentrations of organic material ranged from 0.09 to 0.18 g/cc, minimum and maximum packing. Both the moisture and the inorganic content are expressed as mass ratios relative to the organic mass. Moisture ratios ranged from 0 to 0.8 and inorganic ratios from near 0.04 to 4. They cover the range of conditions that sustain smoldering in peat.

Results are normalized to the initial organic mass. There appears to be no clear dependence of the heat per unit organic mass of peat on organic concentration, moisture, or organic ratios. The average value was 14.79 kJ/g with a standard deviation of 0.198 kJ/g.

Résumé

Les feux couvants, bien qu'ils ne soient pas aussi spectaculaires que les feux de surface, peuvent élever la température du sol minéral, près de la surface, à plus de 400°C pendant plusieurs heures, les températures maximales pouvant dépasser les 600°C. De telles températures peuvent entraîner la décomposition de la matière organique et la mort des organismes minéralisateurs qui fournissent de l'azote sous une forme directement assimilable par les racines. Le facteur sous-jacent contribuant à ces températures est la chaleur de combustion dégagée par la combustion lente qui caractérise un feu couvant.

Des recherches ont été effectuées sur les chaleurs de combustion de diverses teneurs en matières organiques et la teneur en eau et en matières inorganiques a été surveillée par l'intermédiaire de la masse d'oxygène consumée durant la combustion. L'échantillon de feu couvant a été placé dans un cylindre scellé. La quantité d'air introduite dans le cylindre était suffisante pour maintenir une combustion comme celle sur le terrain.

Les teneurs apparentes en matières organiques variaient de ,09 à ,18 g/cc, compacité minimale et maximale respective. L'humidité et la teneur en matières inorganiques sont exprimées par des rapports de masse en fonction de la masse de matières organiques. Les rapports d'humidité variaient de 0 à ,8 et les rapports de matières inorganiques de près de ,04 à 4. Ils couvrent la gamme de conditions qui assurent une combustion lente de la tourbe.

Les résultats sont normalisés en fonction de la masse initiale de matières organiques. Il semble ne pas y avoir de dépendance évidente entre la chaleur de la tourbe par unité masse organique et la teneur en matières organiques et en eau ou les rapports de matières organiques. La valeur moyenne était de 14,79 kJ/g avec une déviation normale de ,198 kJ/g.

Introduction

Smoldering is an alternate form of combustion that occurs in fuel arrays that are more tightly packed than those that sustain flaming. As a broad generalization, there is a transition from flaming to smoldering in common forest fuels when the particle is thin and--from experience--the fuel occupies more that 10% of the volume, e.g., flaming is exhibited in loose litter fuels on the surface of the forest floor and smoldering in the more tightly packed duff below the surface. Duff is similar to peat and is defined as the fermentation and humus layers of the forest floor.

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

The ground fire, as the smoldering fire is named by control specialists, presents no threat in terms of its rate of spread. However, it can persist for days or weeks and later act to initiate a flaming surface fire if it is fanned into momentary flames by a chance gust of wind (Wein 1981). This potential has branded the ground fire as the "hold-over fire."

Duff can act as an effective barrier to downward heat flow from a surface fire if it does not burn. However, when it smolders, the combustion zone can come into intimate contact with the mineral soil interface bringing it to temperatures within the range 300 to 600°C. Wein (1983) reports a temperature of 500°C for smoldering combustion. Heat can then propagate down into the mineral soil raising its temperature. Whether or not the duff burns depends on its moisture and inorganic content (Frandsen 1987).

Directly or indirectly, the heat from the smoldering fire affects the survival of seeds, roots, and the flora and the fauna found in the duff and soil profile that contribute to the health of the soil. It can also have a cleansing effect as well as a stimulus on the existence of pathogens.

The amount of heat transferred to the mineral soil and its associated temperature rise depends on the amount of heat evolved from the smoldering duff and the medium in which the heat is transferred and absorbed. The primary objective of this study was to measure the heat produced by a smoldering fire under simulated field conditions and determine its dependence on the presence of moisture, inorganic material, and the organic concentration of the smoldering medium.

Materials and Methods

Peat was selected as the fuel. It has the texture of duff, is an important ground cover in the wet boreal forest that supports smoldering combustion (Wein 1983), and is a uniform fuel that is commercially available. The lower and upper organic concentrations of the fuel samples were conveniently selected to be 0.09 and 0.18 g/cc. These concentrations are near the lower and upper concentrations that can be easily packed and also correspond to the range of organic concentrations that are normally found in duff. Observations were also made at two intermediate concentrations: 0.12 and 0.15 g/cc.

The moisture and inorganic contents were expressed as mass ratios relative to the organic mass. They are unitless but can be easily converted to densities by multiplying them by the organic concentration. Moisture ratios, R_M, range from 0 to 0.8 at 0.2 intervals and the inorganic ratio, R_I, from 0 to 4 at intervals of 1. All combinations were sampled except those at moisture and inorganic ratios that were not expected to sustain smoldering outside the limits suggested in equation 1 (Frandsen 1987):

$$R_M = 1.1 - 0.25\,R_I \tag{1}$$

Smoldering does not exist for values of R_M and R_I that are greater than the coordinates expressing the linear boundary derived from equation 1.

Water was added to peat--or removed by drying--to achieve selected moisture ratios. Powdered silica was added to obtain inorganic ratios higher than the inherent inorganic content of the peat. Powdered silica (about 240 mesh) was used to ensure that there would be the least amount of chemical interaction between the added inorganic material and the combustion process. The inorganic content in this study is viewed as inert, taking up space and offering no heat to the combustion process.

Observations were made in a random manner to eliminate bias. However, it was not convenient to randomly select moistures over the complete spectrum of conditions. Each moisture ratio required extensive preparation. As a compromise, each moisture was selected randomly and inorganic ratios selected randomly at that moisture ratio.

The rate at which heat is produced is related to the rate of oxygen consumption (Thornton 1917, Huggett 1980) through the following expression.

$$\dot{H} = (Q_c/r)(\dot{M}(in) - \dot{M}(out)) \tag{2}$$

$$\text{setting } \Delta\dot{M} = \dot{M}(in) - \dot{M}(out)$$

for the oxygen mass consumption rate we can then write

$$\dot{H} = (Q_c/r)\,\Delta\dot{M} \tag{3}$$

The term Q_c is the heat content per unit mass of organic material. The term r is the stoichiometry constant of the mass of oxygen that will react with 1 g of organic material. Consequently, the heat conversion term per unit of oxygen is Q_c/r. Huggett (1980) found this conversion term to have a typical value of 13.1 kJ/g for most combustibles covering solids, liquids, and gases.

The experimental sample of peat was contained within an insulated box where it could be ignited and studied as it smoldered. The box, in turn, was placed in a glass cylinder 17 cm in diameter. Both ends of the cylinder were sealed except for an inlet and exit to allow for a flow of air. The flow was held constant at 3.5 g/min (near 3.5 L/min), an amount that was determined to be sufficient to maintain smoldering as experienced in the field.

The sample volume within the insulated combustion box was 5 cm X 5 cm in cross-section and 4 cm deep. The walls of the insulated box were 2.5 cm thick and had thermal properties similar to peat so that heat transferred to the walls was similar to heat transferred within the peat sample. The upper 5 cm X 5 cm exposed surface of the peat was ignited by four rows of resistance heated coils brought to a red glow. The glowing area approximated the area of the peat surface and was held within 5 mm of the surface for 2 min. Each experiment was triggered to start recording data

2 min. before ignition to achieve a zero reference base line.

Four insulated combustion boxes were used throughout the experimental samplings because the walls deteriorated slightly over time. Measurements of the volume were made periodically with sand of a known density so that volumes could be extrapolated for all experimental samplings. Volume was then included as another possible explanatory variable.

The air from the exit port was sampled at 0.1 L/min to determine its reduced oxygen concentration after passing through the combustion chamber. The difference between entering concentration (dry ambient air at 0.2095 L/L) and the final measured concentration was multiplied by the air flow rate through the combustion chamber to obtain the rate of oxygen mass consumption throughout the duration of smoldering.

All of the gaseous products of smoldering combustion must be removed or accounted for to make the comparative measurement of the oxygen concentration necessary for determining the mass of oxygen consumed by the smoldering sample. Carbon dioxide and water are removed by traps installed in the sampling line. Light hydrocarbons are not expected to survive smoldering. Tars and particulates harmful to downstream instruments are also removed by traps. The only product of smoldering that cannot be trapped is carbon monoxide. It was accounted for analytically after its concentration was measured by an infra-red absorption, gas analyzer in line with the sampling stream.

The oxygen sensor is last in the gas sampling line. The active element in the sensor is a zirconium oxide solid electrolyte held at a temperature of 1000°K. Sample air is passed across one side of the electrolyte and a reference standard of dry ambient air across the other. The oxygen concentration of the sample air is obtained according to the Nernst thermodynamic relationship (Kleitz and Fouletier 1976).

A test gas sample moves from the combustion chamber exit port to the oxygen sensor at the end of the sample stream in less than 1 min. All sensors were monitored at 1 min. intervals by a data acquisition system controlled by a computer. Although our knowledge of the smoldering process was limited to a resolution of 1 min., this is small compared to the duration of the experiment. Except for a small fraction of the observations with smoldering durations near 78 min., durations were greater than 100 min. extending up to 245 min. Consequently, the resolution in time was most often less than 1% of the duration of smoldering. All data were converted from sensor signals to physical variables and stored for later analysis. The heat rate was numerically integrated by the trapezoidal rule to obtain the total heat over the duration of smoldering. A total of 190 observations was obtained. This includes additions to the original design for comparison samplings and losses due to those conditions that would not sustain combustion.

All data were reevaluated to obtain the most basic expression of the data: the response variable, heat, and the explanatory variables of organic mass, m_O, inorganic mass, m_I, water mass, m_M, and the volume. It was necessary to obtain a set of independent explanatory variables to apply regression analysis to the data. The previous explanatory variables, the ratios and the organic concentration, were interdependent through the organic mass.

Results

Multiple linear regression analysis of the heat on the organic, inorganic, and the moisture masses, and the volume indicated that there was no significant dependence on the volume as expected. Following the elimination of that variable, the inorganic mass variable was also eliminated because of lack of significance. Finally, the regression was forced through the origin. The final expression was

$$H = a\, m_M + b\, m_O \tag{4}$$

Where $a = -0.8638$ kJ/g and $b = 15.1088$ kJ/g with $R^2 > 0.99$

Dividing the multiple linear regression expression by the organic mass, m_O, leaves a simple linear relationship between the heat content and the moisture ratio (Figure 1):

$$Q_o = a\, R_M + b \tag{5}$$

This simplified expression for estimating the heat content, Q_o, suggests that it is independent of the inorganic ratio and the organic concentration. The heat content shows little dependence on the moisture ratio (Figure 1). The average value for all observations is 14.79 kJ/g with a standard deviation of 0.198 kJ/g. The resultant coefficient of variation is 0.0134 or less than 1.5%. The fact that we see a significant dependence ($P<0.05$) on the moisture ratio when there is such a small overall change in the heat content is an indication of the ability to control conditions in the laboratory.

Plotting the observed heat content against the moisture and inorganic ratio in three dimensions for each organic concentration showed a similarity that supports the lack of dependence on the organic concentration. Because the heat content is independent of the organic concentration, all observations of the heat content can be plotted in one three-dimensional plot against the moisture and inorganic ratio (Figure 2). Although there is some dependence of the heat content on the inorganic ratio it is less than the dependence on the moisture ratio and does not show a general trend as with the moisture ratio.

Multiplying equation (5) by the organic concentration gives us an expression for the heat per unit volume, a

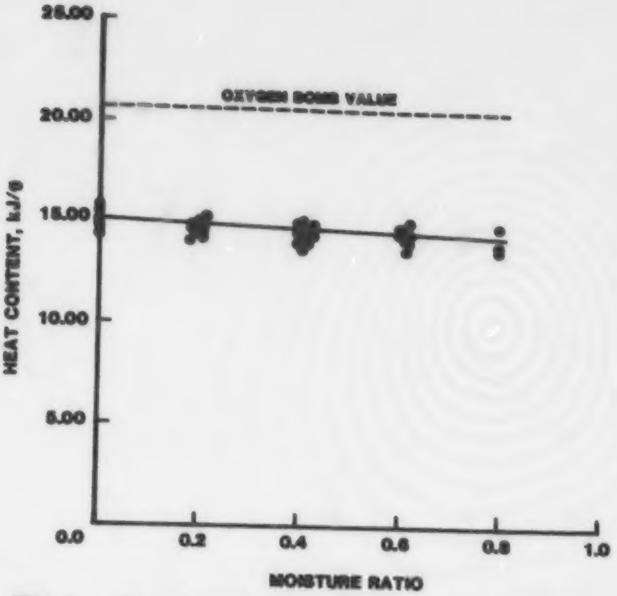


FIG 1. The observed heat content of peat versus the moisture ratio for all observations. A line estimated from the multiple linear regression model is superimposed on the peat observations. The oxygen bomb value (20.70 kJ/g) is shown for comparison.

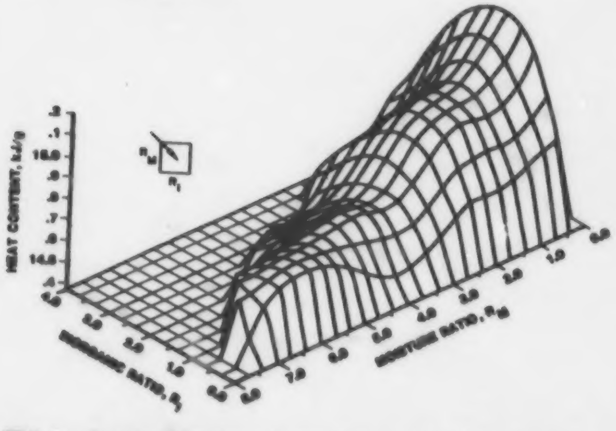


FIG 2. A smoothed three-dimensional plot of the observed heat content of peat versus the inorganic and moisture ratios.

value that is important to the behavior of the smoldering fire.

$$\rho_H = (a\rho_o)R_M + b\rho_o \tag{6}$$

Plotting heat per unit volume, ρ_H, against the moisture ratio, R_M, we expect a family of four lines intersecting the Y-axis at $b\rho_o$ and having slopes of $a\rho_o$ (Figure 3). At any moisture ratio there is a proportionate increase in the heat density with increases in the organic concentration, e.g., there is twice the heat with twice the organic concentration.

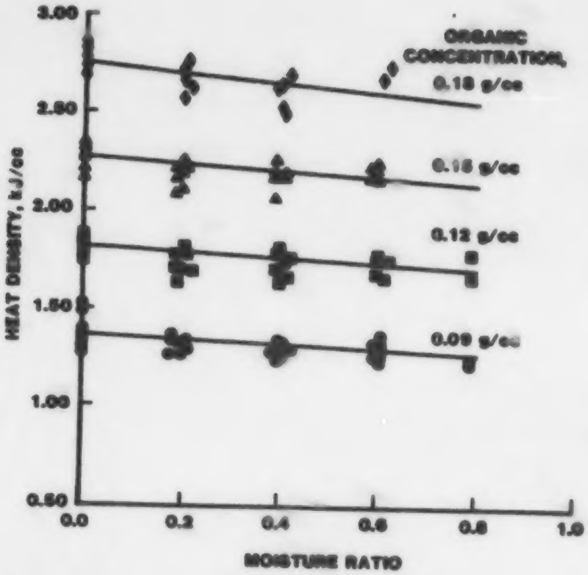


FIG 3. The observed heat density versus the moisture ratio over the applied range of organic concentrations. Each superimposed line was derived from the multiple linear regression model at each value of the organic concentration.

Discussion

The heat content remains constant with increased organic concentration and packing of inorganic material up to four times that of the organic concentration suggesting that oxygen is not a limiting factor in smoldering peat. This is in agreement with evidence reported by Ohlemiller et al. (1979) on flexible polyurethanes: "The smolder process is flexible enough to adapt to a wide range of oxygen-supply levels, including extraordinarily low levels."

When combustion took place, it was complete as evidenced by a residue of only fluffy white ash. The oxygen bomb results for complete combustion of peat was 20.70 kJ/g on an organic mass basis. A comparison of this result with the results above indicates that only 71% of this heat is released under the conditions of this study; conditions that were designed to be comparable with the field. This result suggests that 29% of the heat was retained in unburned residues. They were not evident in the ash residue. Much of this unburned material was deposited on the inside of the combustion chamber as tars. These tars appear in the field as a lacquer finish coating charred needles left from the surface fire.

In summary, these results indicate that the heat released per unit mass of organic matter from peat burned under simulated field conditions is, for all practical purposes, independent of the fuel packing, moisture, and inorganic content.

References

FRANDSEN, W.H. 1987. The influence of moisture and mineral soil on the combustion limits of smoldering forest duff. Can. J. For. Res. 17: 1540-1544.

HUGGETT, C. 1980. Estimation of rate of heat release by means of oxygen consumption measurements. Fire and Materials. 4: 61-65.

KLEITZ, M., and J. FOULETIER. 1976. Technological improvements and accuracy of potentio-metric measurements with zirconia gauges. P. 103-122. In H. Degn, I. Balslev, and R. Brook, eds., Measurement of Oxygen, Elsevier Scientific Pulbishing Co.

OHLEMILLER, T.J., J. BELLAN, and F. ROGERS. 1979. A model of smoldering combustion applied to flexible polyurethane foams. Combust. Flame. 36: 197-215.

THORNTON, W.M. 1917. The relation of oxygen to the heat of combustion of organic compounds. Philosophical Magazine. 33: 196-203.

WEIN, R.W. 1981. Characteristics and suppression of fires in organic terrain in Australia. Aust. For. 44: 162-169.

WEIN, R.W. 1983. Fire behavior and ecological effects in organic terrain. P. 81-95. In R.W. Wein and D.A. Maclean, eds., SCOPE 18: The role of fire in northern circumpolar ecosystems, John Wiley & Sons, New York.

Fire Behavior and Effects in Aspen-Northern Hardwood Stands

M.E. ALEXANDER
Forestry Canada, Northwest Region
Edmonton, Alberta

R.W. SANDO
Department of Natural Resources
St. Paul, Minnesota

Abstract

Six experimental fires were carried out within pure trembling aspen and mixed deciduous stands in the U.S. Lake States region during both spring and late fall (i.e., leafless stage). Available surface fuel loads averaged 2.5 t/ha. *High* to *extreme* burning conditions prevailed as determined by the Canadian Forest Fire Weather Index (FWI) System. Head fire spread rates varied from 1.5 to 8.8 m/min and were highly correlated with the Initial Spread Index component of the FWI System (r = 0.91). Frontal fire intensities ranged from 115 to 672 kW/m. Extensive mortality was observed in trees less than 7.6 cm in diameter at breast height (dbh) while overstory stems greater than 15 cm dbh were seldom affected. Most shrub species were readily top-killed by fire but quickly resprouted. The total number of woody understory stems (deciduous shrubs and small trees) often increased following the fires.

Résumé

Six brûlages expérimentaux ont été effectués, dans des peuplements purs de peupliers faux-tremble et de feuillus mélangés, dans la région des Etats des Grands-Lacs des Etats-Unis. Ces feux, qui ont eu lieu au printemps et tard à l'automne (suite à la chute des feuilles) ont été pratiqués sur des quantités de combustible de surface disponible dont la moyenne était de 2.5 t/ha et ce, sous des conditions de brûlage *élevées* à *extrêmes*, selon l'Indice Forêt-Météo Méthode Canadienne (IFM). Les taux de propagation du feu sous le vent ont varié de 1.5 à 8.8 m/min et montrèrent une haute corrélation avec la composante Indice de Propagation Initiale de la Méthode IFM (r = 0.91). Les intensités du front de flammes ont varié entre 115 et 672 kW/m. Malgré l'importante mortalité des arbres au diamètre à hauteur de poitrine (d.h.p.) inférieur à 7.6 cm, les tiges de l'étage supérieur au d.h.p. excédant 15 cm n'ont cependant que rarement été affectées. La plupart des espèces d'arbustes accusèrent rapidement une mort en cîme due au feu mais ne prirent cependant que peu de temps à repousser. Le nombre total de tiges d'arbustes feuillus et de petits arbres s'est souvent accru, suite au passage du feu.

Introduction

Although trembling aspen (*Populus tremuloides* Michx.) is considered a fire type[1] and a wealth of fire effects literature exists (e.g., Rouse 1986a), surprisingly little empirical fire behavior data is available. In 1968 and 1970, six experimental fires were carried out within pure aspen and mixed hardwood stands in Minnesota and Wisconsin in order to formulate guidelines for the use of prescribed burning in wildlife habitat improvement programs (Sando 1972). These six fires have also proved valuable in the development of a guide to predicting wildfire behavior in the context of the Canadian Forest Fire Danger Rating System (CFFDRS) and contributed to our understanding of prescribed fire effects in northeastern deciduous forests. Originally, the 1964 version of the U.S. National Fire Danger Rating System (Nelson 1964) was used by Sando (1972) to characterize the fire danger conditions. The main purpose of this paper is, in addition, to formally document the CFFDRS indexes associated with these fires. Some of the basic information and data on stand and fuel characteristics, fire weather observations, fire behavior, and initial effects of fire on woody vegetation have been recapitulated, with a minimum of discussion. In contrast to Sando's (1972) original paper, metric units are used here throughout.

Description of Study Areas

Five of the experimental fires were carried out on lands managed by the Minnesota Department of Natural Resources (MDNR) at the Mille Lacs Wildlife Management Area (Table 1) in the central part of the state (Fig. 1). The other experimental fire occurred in central Wisconsin (Fig. 1) on the Necedah National Wildlife Refuge (Table 1), which is administered by the U.S. Department of Interior, Fish and Wildlife Service. The terrain in both study areas is flat. The experimental fire at Necedah (No. 3) took place in an

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

Table 1. Locations, deciduous stand classifications, preburn stand characteristics, and burning dates associated with the six experimental fires carried out in the aspen-northern hardwood fuel type (adapted from Sando 1972).

Experimental fire no.	Study area location	Forest cover type[a]	Stand age (years)	Live tree density (stems/ha)	Basal area (m^2/ha)	Date of burning
1	Mille Lacs	Northern hardwood	52	2570	20.2	30.04.68
2	Mille Lacs	Aspen	22	2540	7.6	02.05.68
3	Necedah	Aspen	45	1327	16.8	27.04.70
4	Mille Lacs	Northern hardwood	34	2637	21.6	06.05.70
5	Mille Lacs	Northern hardwood	54	2209	22.5	08.05.70
6	Mille Lacs	Northern hardwood	54	2703	25.7	19.10.70

[a] The aspen stands exemplify Type 16 (Aspen) in the forest cover type classification of the Society of American Foresters (Eyre 1980) whereas the northern hardwood stands represent a mixture of aspen together with sugar maple, basswood and other shade tolerant tree species.

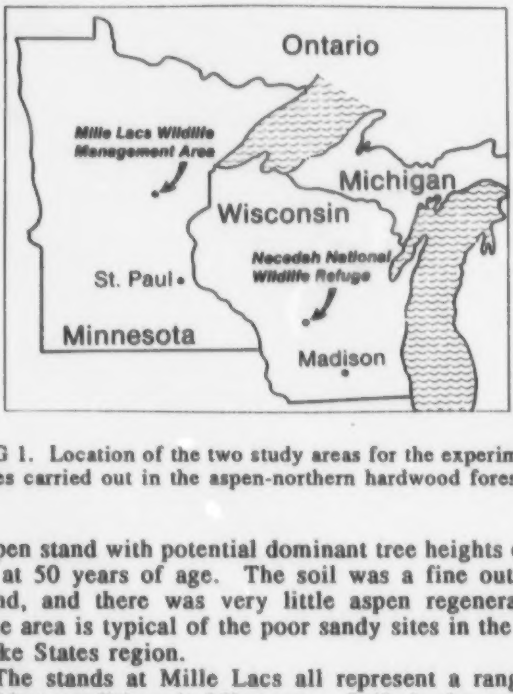

Ontario
Mille Lacs Wildlife Management Area
Michigan
Wisconsin
Necedah National Wildlife Refuge
St. Paul
Minnesota
Madison

FIG 1. Location of the two study areas for the experimental fires carried out in the aspen-northern hardwood forest.

aspen stand with potential dominant tree heights of 14 m at 50 years of age. The soil was a fine outwash sand, and there was very little aspen regeneration. The area is typical of the poor sandy sites in the U.S. Lake States region.

The stands at Mille Lacs all represent a range of habitat conditions in Minnesota. Soils in the area are largely clay loam. The sites studied ranged from poor to medium for aspen, with potential dominant tree heights of 14-17 m at 50 years of age. Much of the Mille Lacs area was originally occupied by eastern white pine (Pinus strobus L.). Three of the experimental fires (Nos. 1, 5 and 6) took place in what were once pure aspen forests but are best described as either mixed or northern hardwood cover types (Table 1). The remaining aspens in these stands were often larger than 25 cm in diameter at breast height (dbh), and most of them by then in their decadent state were being replaced by more shade tolerant tree species such as sugar maple (Acer saccharum Lam.) and basswood (Tila americana L.). Little aspen regeneration was evident prior to burning. One of the experimental fires (No. 2) was carried out in an aspen stand containing some burr oak (Quercus macrocarpa Michx.) for which the site index was 14 m at 50 years of age and the commercial forest potential was very low. The stand area contained many small openings and some large aspen stems located in wet places. These trees had obviously escaped the fire that was responsible for the present stand's origin. Experimental fire No. 4 was carried out in a northern hardwood stand that was considerably younger than the other mixed deciduous types. Again in this stand the aspen was being replaced by sugar maple and other more shade tolerant tree species. A few larger aspen trees that had evidently escaped the stand originating fire were still standing.

Methods

Available fuel loads were estimated from random samples taken of the litter (L) layer of the forest floor using a 30.48 cm x 30.48 cm sampling frame. All of the material within the 929 cm^2 area was collected, placed in paper bags, and returned to the laboratory, where the samples were oven-dried for 24 hours at 105°C and then weighed. Only the hardwood leaf cast and cured herbaceous material were sampled, because the combined fermentation (F) and humus (H) layers of the forest floor contributed very little to the available fuel for combustion of the fires due to their generally high moisture content in the spring and late fall.

On-site weather observations were taken immediately prior to and during the fires. Dry- and wet-bulb temperatures were measured with a sling psychrometer, and relative humidity subsequently was determined from the appropriate psychrometric tables as determined from the elevation above mean sea level (MSL) for the area. Wind speed was measured with a hand-held pilot tube anemometer and at a height of 6.1 m in the open with a recording anemometer.

Unfortunately, on-site weather observations leading up to the fires were not available. For the purpose of fire danger rating calculations, this was not considered to be a major concern because there had been a rain-free period (generally 4-5 days) before the fires very early in the spring and a large amount of rain before the one fall fire. In addition, the relatively flat terrain in both localities would have contributed to uniform heating and atmospheric moisture conditions over fairly large areas. Daily readings of temperature, relative humidity, wind speed, and 24-hour accumulated rainfall measured at 1300 Central Standard Time (CST) were obtained from the closest permanent fire weather stations (see the Appendix). The station at Brainerd, operated by the MDNR, is located 63 km northwest of Mille Lacs. The station at Friendship, operated by the Wisconsin Department of Natural Resources, is located 24 km southeast of Necedah. The weather records utilized in the present study are not listed with the USDA Forest Service's National Fire Weather Data Library (Furman and Brink 1975)[2].

Wind speeds, measured at the U.S. standard of 6.1 m in the open, were adjusted to the CFFDRS standard of 10 m according to the procedure suggested by Turner and Lawson (1978). All weather data were converted to metric units. The six standard components of the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) were calculated by computer program (Van Wagner and Pickett 1985). The standard fuel moisture code starting values following 3 days of snow-free cover in the spring were used (Canadian Forestry Service 1984). The basic observation time in the CFFDRS is 1200 local standard time. The difference of one hour is not considered to be of any great significance (Turner and Lawson 1978).

Fuel moisture content samples were taken immediately prior to ignition of the fires. The samples were collected and placed into metal sampling tins, sealed with masking tape to prevent moisture loss, and returned to the laboratory, where they were oven-dried for 24 hours at 105°C and the moisture content determination was made.

The areas to be burned varied from 4 to 65 ha in size. Several rate of spread (ROS) measurements were made during each fire. The ROS observations were made at selected locations either visually using metal stakes as reference markers or by sound using small exploding devices (i.e., commercially available fireworks) placed at predetermined intervals along a line oriented parallel to the general wind direction during the fire.

Within the areas selected for burning, several circular-shaped 0.04 ha stand inventory plots were located from a random starting point. All trees greater than 2.5 cm dbh on these plots were described and measured before and after burning. The dbh, species, and condition (i.e., live or dead) of each stem were recorded. Five circular-shaped 4.0m^2 shrub and small tree inventory plots were systematically located in each stand inventory plot. The number of only live stems of all shrubs and small trees less than 2.5 cm dbh were recorded by species before and after burning.

Results and Discussion

The six experimental fires took place prior to the initiation of new plant growth in the spring (i.e., between April 27 and May 8) or in the late fall (October 19) after plant growth had ceased (Table 1). The surface fuels were therefore in a dry, cured state. All the experimental fires were ignited around 1300 CST.

STAND AND FUEL FEATURES

The stand age, live tree density, and basal area associated with the experimental fires were from 22-54 years, 1327-2703 stems/ha, and 7.6-25.7 m^2/ha, respectively (Table 1). Deciduous leaf litter was the major surface fuel component in the burning areas. Grasses, ferns, and other herbaceous material also contributed. Available surface fuels averaged 2.47 t/ha. The fuel loads in this study were considerably less than those in other aspen-northern hardwood stands sampled at Mille Lacs (Beyerhelm and Sando 1982). The impact of the lower available fuel volume in this study became evident once the burning began.

BURNING CONDITIONS

The average dry-bulb temperature, relative humidity, and 10-m open wind speed during the experimental fires ranged as folows: 12.7-30.6°C, 22-49%, and 15-28 km/h, respectively (Table 2). The length of time since rain varied from 4 to 9 days. The observed moisture content of fine dead surface fuels was 8.3-14.8%. The daily weather observations preceding each fire have been documented in the Appendix for reasons described elsewhere (Alexander 1982b, 1984).

The three fuel moisture codes and three fire behavior indexes comprising the FWI System, are listed in Table 3 for each experimental fire. They indicate high (FWI 11-22) to extreme (FWI 23+) fire danger according to the classification scheme currently used in Ontario (Stocks et al. 1989).

FIRE BEHAVIOR CHARACTERISTICS

The head fire ROS varied from 1.52 to 8.84 m/min (Table 4), which would be considered moderately slow (i.e., 1-3 m/min) to moderately fast (i.e., 3-10 m/min) (Alexander and Lanoville 1989). The maximum observed ROS was 15 m/min. The importance of wind, within defined limits of fuel moisture, in the propagation of free-burning fires became very evident once the burning began. Several unsuccessful attempts to burn

Table 2. Fire weather observations and fuel moisture conditions associated with six experimental fires carried out in the aspen-northern hardwood forest (adapted from Sando 1972).

Experimental fire no.	Dry-bulb temperature (°C)	Relative humidity (%)	10-m open wind speed (km/h)	Days since rain[a]	Fuel moisture content[b] (% ODW basis)
1	25.6	32	15	7	8.3
2	23.9	22	28	9	9.9
3	30.6	32	28	4	12.0
4	17.2	29	28	4	10.0
5	12.7	49	18	6	11.2
6	18.3	45	28	5	14.8

[a] Amount greater than 0.6 mm.

[b] Pertains to leaf litter and cured herbaceous vegetation. ODW = over-dry weight.

Table 3. Fire danger indexes associated with six experimental fires carried out in the aspen-northern hardwood fuel type.

Experimental fire no.	Fine Fuel Moisture Code (FFMC)	Duff Moisture Code (DMC)	Drought Code (DC)	Initial Spread Index (ISI)	Buildup Index (BUI)	Fire Weather Index (FWI)
1	91.6	20	26	11.5	19	15
2	93.5	29	39	28.7	29	35
3	92.5	26	47	25.2	26	31
4	90.6	20	40	19.2	30	23
5	88.4	24	50	8.4	24	14
6	87.6	8	410	12.4	15	15

[a] Refer to Canadian Forestry Service (1984) for definitions of the six standard components of the Canadian Forest Fire Weather Index (FWI) System.

Table 4. Fire behavior characteristics associated with six experimental fires carried out in the aspen-northern hardwood fuel type (adapted from Sando 1972).

Experimental fire no.	Energy per unit area[a] (kJ/m^2)	Head fire rate of spread (m/min)	Frontal fire intensity (kW/m)
1	4570	1.83	139
2	4560	8.84	672
3	4548	7.01	531
4	4560	1.83	139
5	4553	1.52	115
6	4531	2.13	161

[a] Numerically equal to the product of the low heat of combustion and fuel consumed (Van Wagner 1978). A low heat of combustion value of 18 700 kJ/kg was used and reduced for fuel moisture content (Table 2) equivalent to 24 kJ/kg per moisture content percentage point (Alexander 1982a).

were made on days with weather conditions that would have allowed the fire to spread in many other fuel types. Because of the relatively closed canopy and the light fuel loads in the aspen-northern hardwood stands in the present study, the fires did not spread well, except when the 10-m open winds exceeded ≈18 km/h. The two experimental fires with the highest ROS values (Nos. 2 and 3) occurred in stands that did not have complete crown closure. The wind therefore had more influence on fire spread. Furthermore, the quantity of surface fuels in these two stands was generally greater than the other four and consisted largely of grass and other herbaceous material that burned considerably better than the deciduous leaf litter fuels.

The simple linear correlation coefficient (r) between ISI and head fire ROS for the six observations is 0.913 (significant at the 1% probability level). Some basic analyses of head fire ROS in relation to the ISI are given in Figure 2. Van Wagner's (1973, 1983) ISI-ROS equations tended to overpredict head fire ROS based on the present study results. The coefficient of determination (r^2) values for the linear, exponential, and power function equations given in Figure 2 are 0.83, 0.84 and 0.75, respectively. The standard error of the estimates ($s_{y.x}$) are in turn 1.49, 0.35, and 0.43, respectively. Since these regressions are based on so few data, there is little point in quoting any further statistics of probability or precision. The quantitative information on fire behavior provided by the present study has been combined with other similar experimental data from Ontario and Alberta (e.g., Kiil 1970, Van Wagner 1973, 1975, Perala 1974, Alexander 1982b, Quintilio et al. 1990, Weber 1989), including selected wildfire observations (e.g., Van Wagner 1965, 1973), for use in the derivation of an ISI-ROS relationship for the leafless aspen fuel type (D-1) in the Canadian Forest Fire Behavior Prediction (FBP) System (Alexander et al. 1984, Lawson et al. 1985) (Fig. 3). It's worth noting that the average head fire spread rates observed during the present study represent the highest recorded values for any outdoor experimental fires included in the FBP System data base for Fuel Type D-1. Frontal fire intensities of 115-672 kW/m (Table 4) were calculated on the basis of Byram's (1959) formula (Alexander 1982a):

$$I = Hwr \qquad (1)$$

where I = frontal fire intensity (kW/m), H = fuel low heat of combustion (kJ/kg), w = weight of fuel consumed in the active combustion zone (kg/m²), and r =

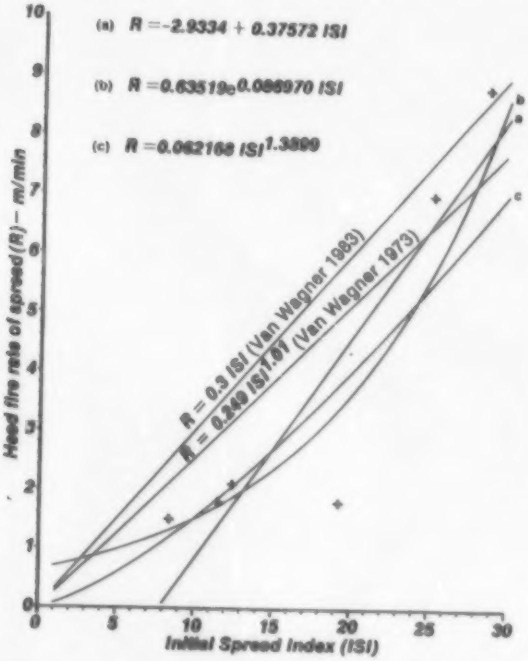


FIG 2. Head fire rate of spread (ROS) as a function of the Initial Spread Index (ISI) according to three commonly used equation forms based on six experimental fires conducted in the aspen-northern hardwood fuel type. The plotted ISI-ROS data points are also included. Existing ISI-ROS relationships for leafless aspen stands, published prior to the introduction of the ROS component of the Canadian Forest Fire Behavior Prediction System in 1984, are included for comparison with results from the present study.

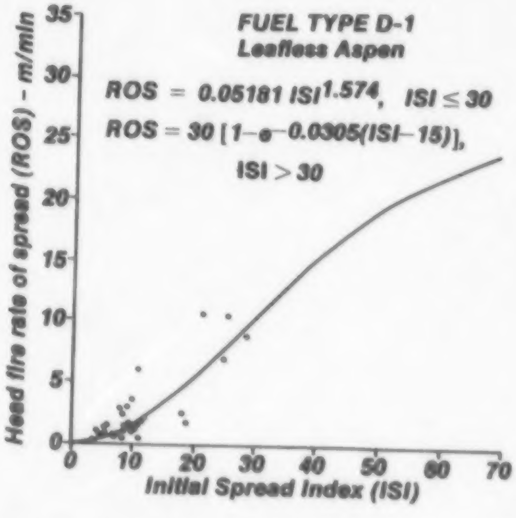


FIG 3. Scattergram of Initial Spread Index (ISI) versus head fire rate of Spread (ROS) observations from experimental fires and wildfires in Fuel Type D-1 (Leafless Aspen) in the 1984 interim edition of the Canadian Forest Fire Behavior Prediction (FBP) System. The S-shaped curve represents the plotted regression equations for this ISI-ROS relationship in the FBP System.

rate of fire spread (m/sec). The predicted flame lengths were 0.7-1.6 m based on Byram's (1959) flame length-fire intensity relationship (from Alexander 1982a):

$$L = 0.0775(I)^{0.46} \quad (2)$$
$$I = 259.833(L)^{2.174} \quad (3)$$

where L = flame length (m) and I = frontal fire intensity (kW/m). These predictions agree reasonably well with the flame lengths actually observed on the fires. Note that equation (3) is simply the inverse of equation (2).

Burning conditions such as those indicated in Tables 2 and 3 would result in uncontrollable fires in most other fuel types but only moderately vigorous fire behavior in aspen-northern hardwood forests during the spring and late fall. For example, according to the ISIs and FWIs reported in Table 3, the expected head fire ROS and frontal fire intensity in mature jack pine (Pinus banksiana Lamb.) stands would be about 5-50 m/min and from perhaps 500 kW/m to in excess of 10,000 kW/m, respectively (Stocks 1989). Two of the fires (Nos. 2 and 3) would have been considered as bordering on moderately difficult to control rating (I = 500-2000 kW/m) from the standpoint of intensity (Alexander and Lanoville 1989), whereas the other four fires would be rated as fairly easy (I < 500 kW/m).

The fire behavior characteristics chart or nomogram (Alexander et al. 1989) is a useful way of interpreting the behavior of free-burning wildland fires having different spread rates and varying degrees of fuel consumption but being of similar intensities (Fig. 4). The amount of fuel potentially available for combustion to a spreading fire in the aspen-northern hardwood fuel type is generally limited because of the distinct differences in the moisture content and bulk density of the litter and duff layers of the forest floor. It is obvious that any variation in frontal fire intensity is generally due to changes in head fire ROS, which in turn is determined primarily by the moisture content of fine dead surface fuels and wind speed. Note that all of the fires plotted in Figure 4 occurred in natural, uncut stands except for that of Perala (1974) which involved moderate amounts of roundwood slash fuels. The "re-burn" documented by Quintilio et al. (1990) did involve a substantial quantity of downed-dead woody fuels.

One documented wildfire not included in Figure 4 is the 1971 Little Sioux Fire in north-eastern Minnesota (Sando and Haines 1972), which made its major run on May 14 under extreme burning conditions. The frontal fire intensity experienced in one aspen-dominated stand was estimated to have exceeded 10,000 kW/m (Ohmann and Grigal 1979). The 1300 CDT fire weather observations at nearby Ely, MN, were (after Sando and Haines 1972): dry-bulb temperature 24.4°C; relative humidity 15%; 10-m open wind 30 km/h; and 10 days since > 0.6 mm of rain. The FWI System components calculated on the basis of the weather data given in Table 1 of Sando and Haines (1972) were: FFMC 95; DMC 45; DC 93; ISI 40; BUI 45; and FWI 53.

FIRE EFFECTS

The above ground effects of a fire on trees and shrubs are related to frontal fire intensity and the vulnerability of the vegetation. Changes in intensity may result in dramatically different fire effects. The vulnerability of woody vegetation is related to several important physical characteristics and also the season and growth activity (i.e., plant phenology). Stem size is an important factor in woody vegetation vulnerability, as demonstrated by many authors (e.g., Ryan and Reinhardt 1988). The two are inversely related, and this was evident from the results obtained in the present study (Table 5). The direct, fire-induced tree mortality occurred primarily in the smallest dbh size classes (i.e., < 7.6 cm). Trees larger than about 8 cm

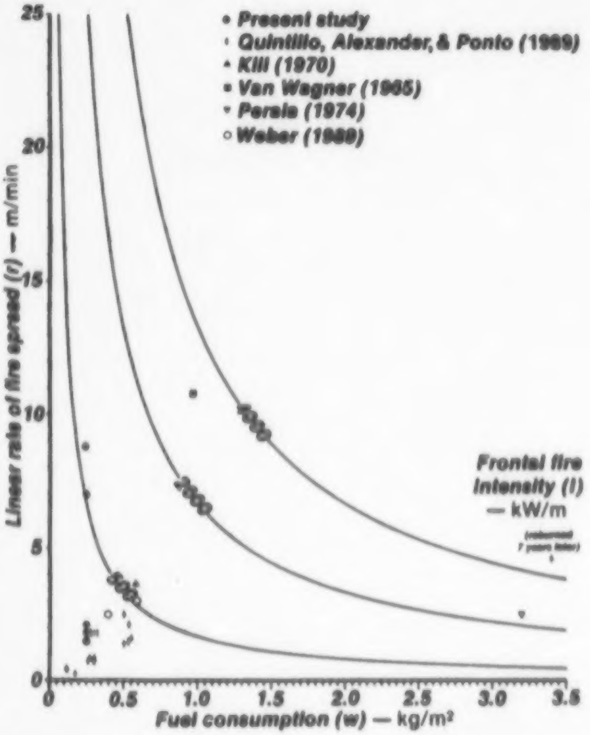


FIG 4. Head fire spread rate and fuel consumed plotted in relation to four distinct levels of frontal fire intensity for six experimental fires conducted in the aspen-northern hardwood fuel type (net heat of combustion = 18 000 kJ/kg). Other experimental fires and wildfires in similar deciduous fuel complexes, in the leafless state, are included for comparison with results from the present study.

Table 5. Tree mortality associated with experimental fires carried out in six aspen-northern hardwood stands (after Sando 1972). The diameter at breast height (dbh) stem tallies were made at the end of the first growing season following fire.

Experimental fire no.	Dbh size class[a]		
	2.5-5.1 cm (%)	5.1-7.6 cm (%)	7.6-10.2 cm (%)
1	91	52	-[b]
2	90	81	65
3	94	47	57
4	64	71	49
5	33	21	11
6	2	1	0

[a] The stems were originally tallied by 1-inch dbh size classes (i.e., 1-2 in., 2-3 in., and 3-4 in.).

[b] Not sufficient data.

dbh were seldom killed, and negligible mortality occurred in trees larger than 15 cm dbh. Brown and Simmerman (1986) have suggested that flame lengths of at least 0.52-0.64 m, or frontal fire intensities of 63-98 kW/m accordingly to equation (3), are required to kill aspen trees in the western U.S. No dbh size classes were specified, however. The broadleaf tree species that occur in both study areas appear to be equally vulnerable to fire with the exception of burr oak, which has a relatively thick bark whose insulating qualities help to reduce the killing effect of the fires (Rouse 1986b).

Shrub stems were easily top-killed by fire, but regrowth by sprouts quickly occurred and was quite prolific in some cases (Fig. 5). The frequency of shrub stems is thereby often increased by burning. Red-osier dogwood (*Cornus stolonifera* Michx.) did not increase dramatically, except where most of the overstory was killed by the fire; in some cases it was reduced by the fire (Fig. 5). Most of the deciduous tree species killed by fire promptly sprouted. Most eastern hardwoods share the ability to regenerate vegetatively (Johnson 1983). The advanced reproduction of sugar maple and other shade tolerant species was temporarily eliminated or their occurrence reduced. The regeneration of aspen was stimulated by fire. Aspen responded to the burning with prolific root suckering. Several instances were noted where aspen suckers originated up to 15 m from the nearest parent tree. Consequently, the total number of woody stems often increased following the fires as a result of the aspen suckering and shrub sprouting. The effects of the five spring fires on the shrub and small tree layer, conducted just prior to the initiation of new growth, were much greater than those observed following the one fall fire (Fig. 5). The average increase in total stem density for the spring fires was 67%, with a range of 22-152%. There was a 10% decrease associated with the fall fire.

IMPLICATIONS FOR PRESCRIBED FIRE MANAGEMENT

The use of prescribed burning for the management of wildlife habitat in aspen-northern hardwood stands not subjected to cutting poses a difficult problem because of the nature of the fuel complex. Burning conditions must be much more severe than in other fuel types for success. The most important variable is wind speed. Without sufficient wind the fire will not spread well in the light fuels found in these stands. The results of this study indicate that it is important to treat aspen stands with fire before they are of advanced age. An alternative technique is to cut the stands before burning. Where commercial harvesting is not possible, fire must be used before the average dbh of the trees in a stand exceed at 13 cm. Fuels that will support a fire of adequate intensity to kill the overstory trees are generally much greater in young stands, while the dominant trees will have a smaller average dbh and consequently thinner bark at or near ground level, thereby increasing the susceptibility to girdling by surface fires. The prescribed fire manager must therefore carefully evaluate fuel and stand conditions for successful burning. Sando (1972) has provided some burning prescriptions in terms of basic fire weather elements. The frequencies of suitable weather conditions for prescribed burning have been reported elsewhere (e.g., Sando 1969, Beyerhelm and Irving 1980).

Conclusions

Sando (1972) provided a reasonably well-documented account of six fires conducted primarily for reasons other than the scientific study of forest fire behavior. No doubt the additional knowledge gained about certain fire effects in relation to documented burning conditions and quantified fire behavior has or will eventually lead to improved prescriptions for the use of fire in forest vegetation management (e.g., Beyerhelm 1979). More important perhaps is the fact that the quantitative data on fire behavior as furnished by Sando (1972) have resulted in a small but direct contribution to the development of the CFFDRS. The ROS component of the FBP System was developed largely from experimental burning projects and wildfire investigations carried out in Canada (e.g., Alexander and Lanoville 1987, Stocks 1989); however, the empirical data base associated with the FBP System was also supplemented with a few relevant observations adapted from U.S. sources (e.g., Alexander 1982b, 1984). Field research to gather experimental fire behavior data can be time consuming and expensive. This paper serves as an example of how to capture outside information for FBP System data base purposes. If the basic weather observations are available, then it is possible to redescribe the burning conditions of previously documented forest fires in terms of the weather-dependent components of the FWI System and thereby permitting possible correlations with actual ignition probabilities,

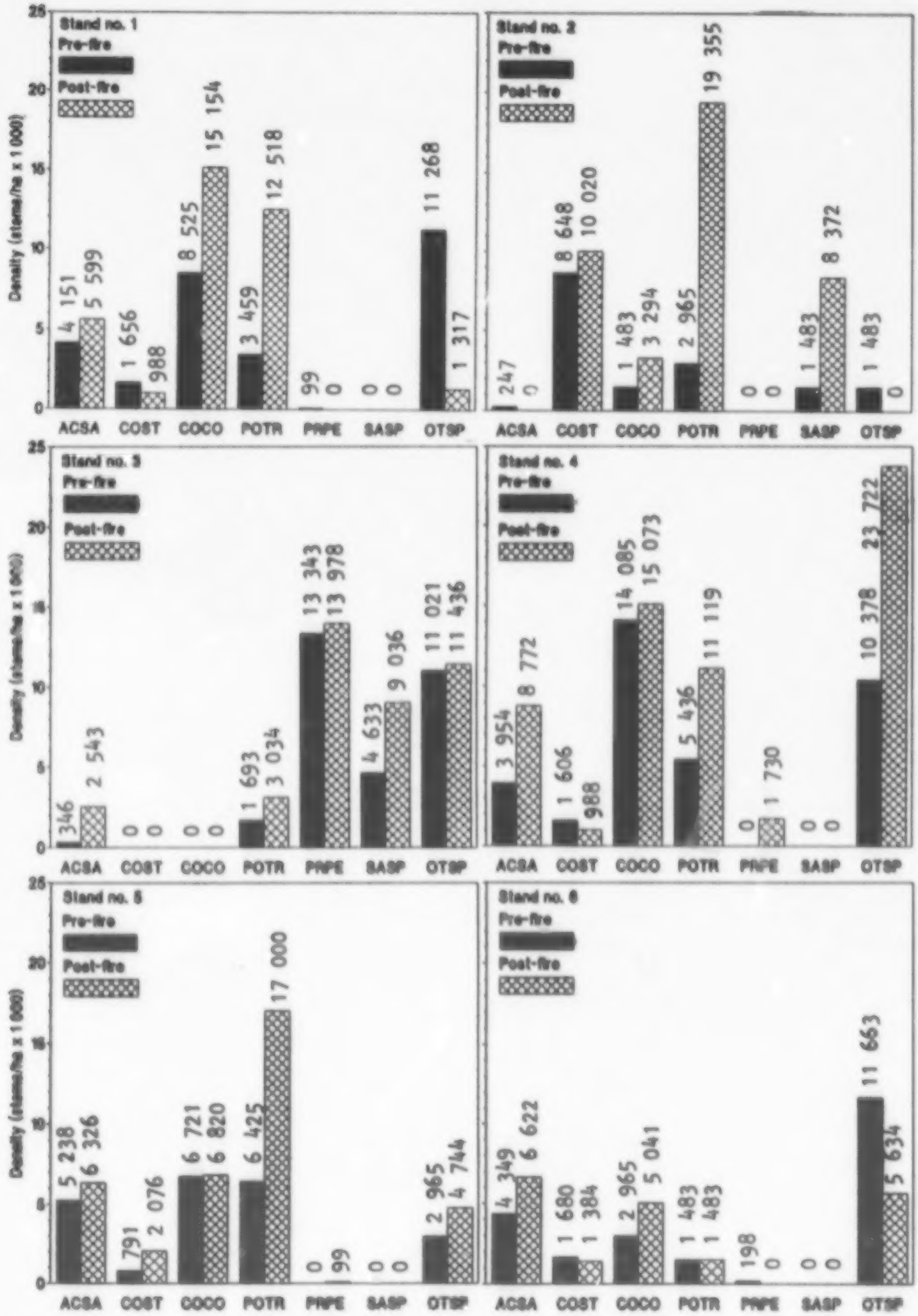


Fig 5. Shrub and small tree stem densities associated with the experimental fires carried out in six aspen-northern hardwood stands (adapted from Sando 1972). Stem tallies were made at the end of the first growing season following fire. The actual stem density is given at the top of each plotted bar. Abbreviations used are: ASCA = *Acer saccharum* Lam. (sugar maple); COST = *Cornus stolonifera* Michx. (red-osier dogwood); COCO = *Corylus cornuta* Marsh. (beaked hazel); POTR = *Populus tremuloides* Michx. (trembling aspen); PRPE = *Prunus pensylvanica* L. (pin cherry); SASP = *Salix* spp. (willow); and OTSP = other species. There is an arithmetic error in Sando's (1972) Table 3 shrub data summary that was in turn repeated in Table 3.1 of Beyerhelm (1979). For Stand 2 (postburn), the total number of stems for all species is given as 24,442 stems per acre. This should have been 16,609 stems per acre.

fire behavior characteristics, and fire impact/effects in specific fuel types.

Acknowledgements

The experimental fires reported in this paper were originally documented by R.W. Sando while employed as a Research Forester with the USDA Forest Service, North Central Forest Experiment Station (NCFES), St. Paul, MN. D.A. Haines, NCFES, East Lansing, MI, kindly arranged for the provision of the weather data from Friendship, WI. The assistance of D. Lyzun, M.E. Maffey, J.K. Samoil, E. Schiewe, and J. Simunkovic of the Northern Forestry Centre (NoFC) in the preparation of this paper is gratefully appreciated. Z. Chrosciewicz (NoFC) and B.D. Lawson (Pacific Forestry Centre) reviewed the draft manuscript.

References

ALEXANDER, M.E. 1982a. Calculating and interpreting forest fire intensities. Can. J. Bot. 60:349-357.

ALEXANDER, M.E. 1982b. Fire behavior in aspen slash fuels as related to the Canadian Fire Weather Index. Can. J. For. Res. 12:1028-1029.

ALEXANDER, M.E. 1984. Prescribed fire behavior and impact in an eastern spruce-fir slash fuel complex. Can. For. Serv. Res. Notes 4:3-7.

ALEXANDER, M.E., AND R.A. LANOVILLE. 1987. Wildfires as a source of fire behavior data: a case study from Northwest Territories, Canada. In Postprint volume, ninth conference on fire and forest meteorology. American Meteorological Society, Boston, MA. pp. 86-93.

ALEXANDER, M.E., AND R.A. LANOVILLE. 1989. Predicting fire behavior in the black spruce-lichen woodland fuel type of western and northern Canada. Forestry Canada, Northern Forestry Centre, Edmonton, AB, and Government of the Northwest Territories, Department of Renewable Resources, Territorial Forest Fire Centre, Fort Smith, NT. Poster (with text).

ALEXANDER, M.E., B.D. LAWSON, B.J. STOCKS, AND C.E. VAN WAGNER. 1984. User guide to the Canadian Forest Behavior Prediction System: rate of spread relationships. Interim edition. Environment Canada, Canadian Forestry Service, Fire Danger Group, Ottawa, ON. [First printing July 1984; revision and second printing Sept. 1984.]

ALEXANDER, M.E., B.J. STOCKS, AND B.D. LAWSON. 1989. Fire behavior in black spruce-lichen woodland: the Porter Lake project. For. Can. Inf. Rep. NOR-X-310.

BEYERHELM, C.D. 1979. Guidelines for the implementation of a prescribed burning program at the Mille Lacs Wildlife Management Area. M.Sc. Plan B Paper, University of Minnesota, College of Forestry, St. Paul, MN.

BEYERHELM, C.D., AND F.D. IRVING. 1980. Frequency of suitable prescribed burning weather in east-central Minnesota. Univ. Minn. Agric. Exp. Stn. Tech. Bull. 327.

BEYERHELM, C.D., AND R.W. SANDO. 1982. Regression estimation of litter and one hour timelag fuel loading in aspen-northern hardwood stands. For. Sci. 28:177-180.

BROWN, J.K., AND D.G. SIMMERMAN. 1986. Appraising fuels and flammability in western aspen: a prescribed fire guide. USDA For. Serv. Gen. Tech. Rep. INT-205.

BYRAM, G.M. 1959. Combustion of forest fuels. In K.P. Davis, ed., Forest fire: control and use. McGraw-Hill Inc., New York.

ANONYMOUS. 1984. Tables for the Canadian Forest Fire Weather Index System. 4th ed. Can. For. Serv. For. Tech. Rep. 25.

EYRE, F.H., (Ed.). 1980. Forest cover types of the United States and Canada. Society of American Foresters, Washington, DC.

FURMAN, R.W., AND G.E. BRINK. 1975. The national fire weather data library: what it is and how to use it. USDA For. Serv. Gen. Tech. Rep. RM-19.

JOHNSON, V.J. 1983. Ambivalent effects of fire in eastern broadleaf forests. In America's hardwood forests - opportunities unlimited. Proceedings of the 1982 convention of the Society of American Foresters. Society of American Foresters, Washington, DC. SAF Publ. 83-04. pp. 153-156.

KIIL, A.D. 1970. Effects of spring burning on vegetation in old partially cut spruce-aspen stands in east-central Alberta. Can. For. Serv. Inf. Rep. A-X-33.

LAWSON, B.D., STOCKS, B.J., ALEXANDER, M.E., AND C.E. VAN WAGNER. 1985. A system for predicting fire behavior in Canadian forests. In Proceedings of the eighth conference on fire and forest meteorology. Edited by L.R. Donoghue and R.E. Martin. Society of American Foresters, Bethesda, MD. SAF Publ. 85-04. pp. 6-16.

MERRILL, D.F., AND M.E. ALEXANDER., (Ed.), 1987. Glossary of forest fire management terms. 4th ed. Natl. Res. Counc. Can., Can. Comm. For. Fire Manage., Publ. NRCC No. 26516.

NELSON, R.M. 1964. The national fire danger rating system. USDA For. Serv. Res. Pap. SE-13.

OHMANN, L.F., AND D.F. GRIGAL. 1979. Early revegetation and nutrient dynamics following the 1971 Little Sioux Forest Fire in northeastern Minnesota. For. Sci. Monogr. 21:1-80.

PERALA, D.A. 1974. Prescribed burning in an aspen-mixed hardwood forest. Can. J. For. Res. 4:222-228.

QUINTILIO, D., M.E. ALEXANDER, AND R.L. PONTO. 1990. Spring fires in a semi-mature trembling aspen stand, central Alberta. For. Can. Inf. Rep. NOR-X [in press].

ROUSE, C. 1986a. Fire effects in northeastern forests: aspen. USDA For. Serv. Gen. Tech. Rep. NC-102.

ROUSE, C. 1986b. Fire effects in northeastern forests: oak. USDA For. Serv. Gen. Tech. Rep. NC-105.

RYAN, K.C., AND E.D. REINHARDT. 1988. Predicting postfire mortality of seven western conifers. Can. J. For. Res. 18: 1291-1297.

SANDO, R.W. 1969. Prescribed burning weather in Minnesota. USDA For. Serv. Res. Pap. NC-28.

SANDO, R.W. 1972. Prescribed burning of aspen-hardwood stands for wildlife life habitat improvement. Paper presented at the 34th midwest fish and wildlife conference, December 10-13, 1972, Des Moines, IA.

---

[1] A particular forest cover or vegetation type that commonly follows or is otherwise dependent on fire (Merrill and Alexander 1987).

[2] R.L. Bradshaw, Computer Programmer Analyst, USDA Forest Service, Boise, Interagency Fire Center, Boise, Idaho, personal communication.

SANDO, R.W., AND D.A. HAINES. 1972. Fire weather and behavior of the Little Sioux Fire. USDA For. Serv. Res. Pap. NC-76.

STOCKS, B.J. 1989. Fire behavior in mature jack pine. Can. J. For. Res. 19:783-790.

STOCKS, B.J., B.D. LAWSON, M.E. ALEXANDER, C.E. VAN WAGNER, R.S. MCALPINE, T.J. LYNHAM, AND D.E. DUBÉ. 1989. Canadian Forest Fire Danger Rating System: an overview. For. Chron. 65:450-457.

TURNER, J.A., AND B.D. LAWSON. 1978. Weather in the Canadian Forest Fire Danger Rating System: a user guide to national standards and practices. Can. For. Serv. Inf. Rep. BC-X-177.

VAN WAGNER, C.E. 1965. Story of an intense crown fire at Petawawa. Pulp Pap. Mag. Can. Woodland Rev. Sect. 66(8):358-361.

VAN WAGNER, C.E. 1973. Rough prediction of fire spread rates by fuel type. Can. For. Serv. Inf. Rep. PS-X-42. [revised 1980.]

VAN WAGNER, C.E. 1975. Convection temperatures above low intensity forest fires. Can. For. Serv. Bi-mon. Res. Notes 31:21.

VAN WAGNER, C.E. 1978. Metric units and conversion factors for forest fire quantities. Can. For. Serv. Inf. Rep. PS-X-71.

VAN WAGNER, C.E. 1983. Fire behavior in northern conifer forests and shrublands. In R.W. Wein and D. A. MacLean, ed., SCOPE 18: The role of fire in northern circumpolar ecosystems. John Wiley & Sons, Chichester, England. pp. 65-80.

VAN WAGNER, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Can For. Serv. For. Tech. Rep. 35.

VAN WAGNER, C.E., AND T.L. PICKETT. 1985. Equations and FORTRAN program for the Canadian Forest Fire Weather Index System. Can. For. Serv. For. Tech. Rep. 33.

WEBER, M.G. 1989. Response of immature aspen ecosystems to cutting and burning in relation to vernal leaf flush. For. Ecol. Manage. 30:(in press).

APPENDIX:

DAILY FIRE WEATHER OBSERVATIONS RECORDED AT 1300 CST

Table A.

Data recorded at Brainerd, MN, from April 22 to May 1, 1968, April 26 to May 7, 1970, and October 12-18, 1970 (station elevation: 366 m MSL).

Calendar date (1968/1970)	Dry-bulb temperature (°C)	Relative humidity (%)	10-m open wind speed (km/h)	24-h rain (mm)
April 22	7.2	79	24	0.5
23	2.8	74	48	21.8
24	4.4	53	30	0.0
25	9.4	32	13	0.0
26	14.4	33	18	0.0
27	12.2	43	17	0.0
28	14.4	42	2	0.0
29	18.3	25	28	0.0
30	25.0	27	11	0.0
May 1	22.2	32	15	0.0
April 26	18.9	30	14	0.0
27	17.2	65	13	3.6
28	19.4	58	24	12.4
29	18.9	66	5	0.0
30	10.6	46	16	0.0
May 1	0.0	90	8	0.5
2	12.8	39	18	2.0
3	17.8	41	31	0.0
4	13.9	32	10	0.0
5	8.9	31	16	0.0
6	13.9	32	18	0.0
7	18.9	42	11	0.0
Oct. 13[a]	6.7	93	22	27.9
14	6.7	64	20	1.5
15	5.0	61	11	0.0
16	11.1	41	17	0.0
17	14.4	52	17	0.0
18	13.9	51	4	0.0

[a] The DMC and DC on October 12, 1970, were 6 and 537, respectively.

Table B. Data Recorded at Friendship, WI, April 7-26, 1970 (station elevation: 291 m MSL).

Calendar date (1970)	Dry-bulb temperature (°C)	Relative humidity (%)	10-m open wind speed (km/h)	24-h rain (mm)
April 7	16.7	33	24	0.0
8	15.6	27	30	0.0
9	11.1	25	35	0.0
10	6.7	31	17	0.0
11	7.2	51	20	0.0
12	3.3	75	22	1.8
13	4.4	61	22	1.8
14	14.4	29	15	3.3
15	18.3	32	22	0.0
16	17.8	24	22	4.1
17	9.4	49	18	0.0
18	6.1	49	15	0.0
19	4.4	68	24	0.0
20	4.4	76	22	16.8
21	6.1	56	26	0.5
22	6.7	78	26	0.0
23	11.7	42	26	1.8
24	15.6	27	22	0.0
25	23.9	25	24	0.0
26	26.1	35	17	0.0

1978 National Fire Danger Rating System Revisions

R. E. BURGAN
Southeastern Forest Experiment Station
Macon, Georgia

Abstract

The 1978 National Fire Danger Rating System (NFDRS) has been revised to improve its performance in the relatively humid environment of the Eastern United States. The issues addressed were:

- Improve the capability of the NFDRS to respond to drought.
- Provide flexibility to reflect greening and curing of live fuels.
- Correct the problem of overrating fire danger after rainfall.
- Correct the problem of overrating fire danger in the autumn.
- Adjust the fuel models to better predict fire danger in humid areas.

Factors causing these problems and operational impacts are discussed. System changes are defined, and comparisons between the results here and with the original 1978 NFDRS are illustrated.

Résumé

Le Système national de détection de dangers d'incendie de 1978 (NFDRS) a été revu afin d'améliorer son rendement dans le milieu relativement humide de l'est des États-Unis. Les questions abordées étaient les suivantes:

- Améliorer la capacité du NFDRS en période de sécheresse
- Le rendre plus flexible pour prendre en compte la période de verdissement et d'assèchement des matières combustibles vivantes
- Remédier à la surestimation des dangers d'incendie après une chute de pluie
- Remédier à la surestimation des dangers d'incendie à l'automne
- Ajuster les modèles sur les combustibles pour mieux prédire les dangers d'incendie dans les régions humides

Les facteurs à l'origine de ces problèmes et les incidences opérationnelles sont examinés, les modifications du systèmes sont définies, des comparaisons entre ces resultats et avec le NFDRS original de 1978 sont illustrées.

Introduction

The 1978 National Fire Danger Rating System (NFDRS) (Deeming et al. 1977) has been used without modification since it was implemented. Users in the eastern U. S. and Alaska have felt for some time that the system did not respond properly in their areas. A national meeting was convened at Harper's Ferry, West Virginia, in 1986 to discuss their concerns. The consensus of the meeting was that fire researchers should revise the system to solve the most serious shortcomings, and that a revised system should be implemented as soon as possible. The highest priority research issues were:

- Improve the capability of the NFDRS to respond to drought in humid environments.
- Provide flexibility to reflect greenup and curing of live fuels.
- Correct the problem of overrating fire danger after rainfall.
- Correct the problem of overrating fire danger in the autumn.
- Adjust the fuel models to better represent fire danger in humid climates.

The System has been revised and is called the 1988 National Fire Danger Rating System. This paper presents each research issue in turn, discusses the system revisions, and graphically compares several outputs from the 1978 and 1988 NFDR Systems. These comparisons are based on weather data from Athens, Georgia, and assume fuel model C. Athens is on the Piedmont Plateau in north-central Georgia. Fuel model C applies to open pine stands with modest amounts of needle litter, grasses, and shrubs. Specific fuel loadings for the 20 recognized fuel models are summarized in Table 1.

Problems and Solutions

RESPONSE TO DROUGHT

The 1978 NFDRS relies upon the 1,000-hour fuel moisture to track changes in large dead fuel moisture,

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

Table 1 .--1978 NFDRS fuel model descriptions

Fuel model parameters	Fuel model A	B	C	D	E	F	G	H	I	J	K	L	N	O	P	Q	R	S	T	U
Load (tons/acre)																				
1-hour dead	0.2	3.5	0.4	2.0	1.5	2.5	2.5	1.5	12.0	7.0	2.5	0.25	1.5	2.0	1.0	2.0	0.5	0.5	1.0	1.5
10-hour dead	--	4.0	1.0	1.0	0.5	2.0	2.0	1.0	12.0	7.0	2.5	--	1.5	3.0	1.0	2.5	0.5	0.5	0.5	1.5
100-hour dead	--	0.5	--	--	0.25	1.5	5.0	2.0	10.0	6.0	2.0	--	--	3.0	0.5	2.0	0.5	0.5	--	1.0
1000-hour dead	--	--	--	--	--	--	12.0	2.0	12.0	5.5	2.5	--	--	2.0	--	1.0	--	0.5	--	--
Woody	--	11.5	0.5	3.0	0.5	9.0	0.5	0.5	--	--	--	--	2.0	7.0	0.5	4.0	0.5	0.5	2.5	0.5
Herbaceous	0.3	--	0.8	0.75	0.5	--	0.5	0.5	--	--	--	0.5	--	--	0.5	0.5	0.5	0.5	0.5	0.5
Surface-area-to-volume ratio (1/ft)																				
1-hour dead	3,000	700	2,000	1,250	2,000	700	2,000	2,000	1,500	1,500	1,500	2,000	1,600	1,500	1,750	1,500	1,500	1,500	2,500	1,750
10-hour dead	--	109	109	109	109	109	109	109	109	109	109	--	109	109	109	109	109	109	109	109
100-hour dead	--	30	30	--	30	30	30	30	30	30	30	--	--	30	30	30	30	30	--	30
1000-hour dead	--	8	--	--	--	--	8	8	8	8	8	--	--	8	--	8	8	8	--	--
Woody	--	1,250	1,500	1,500	1,500	1,250	1,500	1,500	--	--	--	--	1,500	1,500	1,500	1,200	1,500	1,200	1,500	1,500
Herbaceous	3,000	--	2,500	1,500	2,000	--	2,000	2,000	--	--	--	2,000	--	1,500	2,000	1,500	2,000	1,500	2,000	2,000
Heat content (all fuels)																				
(Btu/lb)	8,000	9,500	8,000	9,000	8,000	9,500	8,000	8,000	8,000	8,000	8,000	8,000	8,700	9,000	8,000	8,000	8,000	8,000	8,000	8,000
Moisture of Extinction (%)																				
Dead	15	15	20	30	25	15	25	20	25	25	25	15	25	30	30	25	25	25	15	20
Fuel Bed Depth (ft)	0.8	4.5	0.75	2.0	0.4	4.5	1.0	0.3	2.0	1.3	0.6	1.0	3.0	4.0	0.4	3.0	0.25	0.4	1.25	0.5
Wind adjustment factor	0.6	0.5	0.4	0.4	0.5	0.5	0.4	0.4	0.5	0.5	0.5	0.6	0.6	0.5	0.4	0.4	0.4	0.6	0.6	4
SC_{max}	301	58	32	68	25	24	30	8	65	44	23	178	167	99	14	59	6	17	96	16

thus reflecting the effect of normal annual wetting and drying cycles. The 1,000-hour moisture curve for Stonyford Ranger Station in California shows that this concept works very well for arid locations, but the 1,000-hour curve for Athens shows much less seasonal fluctuation, even though 1986 was a very dry year in Georgia (Figure 1). In the absence of rain, relative humidity strongly influences the 100- and 1000-hour fuel moisture calculations. In the Eastern United States, humidity recovery is very good at night, and daytime relative humidity generally does not drop below 40 percent. The Athens data illustrate that fuel moisture in large fuels reaches equilibrium at around 15 or 16 percent, even in the driest years.

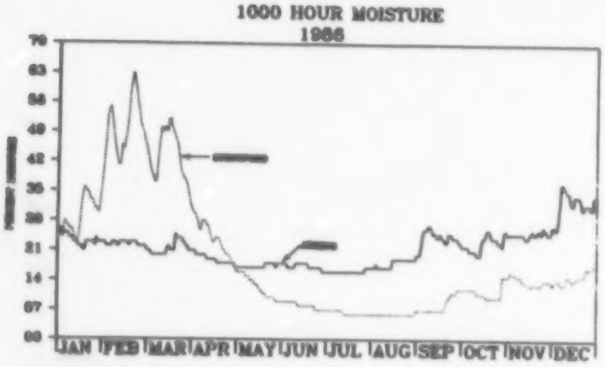


FIG. 1.--The 1,000-hour timelag fuel moisture comparisons for a relatively dry western environment (Stonyford Ranger Station, CA) and a humid eastern environment (Athens, GA).

No attempt was made to modify the theory behind these calculations. Instead, the Keetch-Byram Drought Index (KBDI) (Keetch and Byram 1968) has been added to the NFDRS, both as a reference number for the user and as a method to modify dead fuel load to account for the effect of drought on fuel availability.

Fuel models developed for the 1988 NFDRS include an additional dead fuel load to serve as a fuel reservoir to be added as drought increases. The concept is that as drought progresses, more dead fuel becomes available as drying proceeds through the forest floor profile. Thus, the dead fuel load becomes a dynamic indicator (analog), capable of reflecting drought conditions.

Figure 2 illustrates the functional relationship. No extra dead fuel is transferred into the fuel model until the Keetch-Byram Drought Index increases above 100. Then it is added linearly, until all of the dead fuel reservoir is added by the time the Keetch-Byram Drought Index has reached its maximum value of 800. The added fuel is distributed in proportion to the predrought dead fuel loads, with depth increased to preserve the packing ratio.

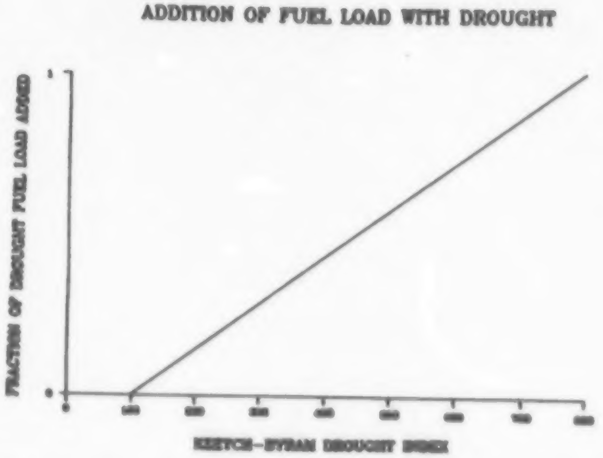


FIG. 2.--Addition of drought fuel load as a function of the Keetch-Byram Drought Index.

Figure 3 illustrates the transfer of a portion of the drought fuel load to the 10-hour fuel class for Athens in 1986. The 1978 NFDRS model C 10-hour fuel load remains constant at 1 ton per acre, but with the 1988 NFDRS model C the 10-hour load increases to nearly 2 tons per acre during the peak drought period. The other dead fuel loads are also increased proportionately.

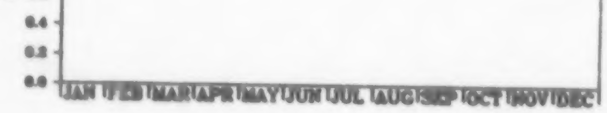


FIG. 3.--As the Keetch-Byram Drought Index fluctuates above 100, dead fuel load in the 1988 NFDRS changes but it remains constant for the 1978 NFDRS.

GREENING AND CURING OF LIVE FUELS

In the 1978 NFDRS, the date at which greening starts is defined by the user, but the length of the greenup period is predetermined as a function of climate class. Fall curing is assumed to occur in one day, following a freeze. These assumptions are not particularly realistic.

The revised NFDRS implements separate greenness factors for live herbaceous and live woody fuels. These factors are 0 when the grasses are cured and the shrubs are dormant, and 20 when they are fully green. Intermediate values indicate intermediate greenness levels. Because live woody and live herbaceous vegetation may respond to moisture stress at different times, the user must enter both grass and shrub greenness factors daily. The live woody greenness factor for Athens 1986 data is shown at the bottom of figure 4. The live woody greenness factor is varied during the year to reflect the effect of the varying levels of drought on live woody fuel moisture.

The upper portion of figure 4 compares 1978 and 1988 NFDRS live woody moistures, with the difference between them reflecting modification of standard live woody moisture calculations by the greenness factor. Notice also that the revised NFDRS permits gradual moisture reduction in the fall.

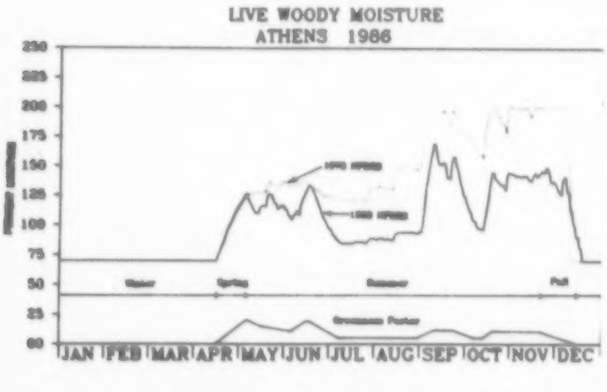


FIG. 4.--The 1988 NFDRS has an improved capability to calculate reduced live fuel moisture through the use of reduced greenness factor values. The y-axis scale references both percent moisture and greenness factor values.

OVERRATING FIRE DANGER AFTER RAINFALL

The 1978 NFDRS can overrate fire danger after rainfall, especially if strong winds or low humidities occur after a frontal passage. If fuel moisture sticks are not used to measure 10-hour timelag fuel moisture, fine dead fuel moisture calculations are not affected by precipitation unless it is occurring at observation time. If 10-hour sticks are used, they provide a 20 percent influence on the fine dead fuel moisture calculation. In either case, experience has shown that estimates of fine dead fuel moistures are often too low. Underestimation is corroborated by recent research (Anderson 1985) which shows that most fine dead fuels actually have a response time closer to 10 hours than to 1 hour. For these reasons the 1988 NFDRS has an option to set the fine dead fuel moisture equal to the 10-hour timelag fuel moisture.

Figure 5 shows that measured fuel stick moistures are often higher than calculated 1-hour moisture values, and are more responsive to rainfall events. The revised NFDRS lets the user decide whether to set the 1-hour fuel moisture equal to the 10-hour fuel moisture every day, or just on the day of and the day after at least 0.1 inch of rain. In addition, to reduce the effect of strong winds behind a cold front, the midflame windspeed is reduced 70 percent on the day of and day after rain. Thus, the system is less sensitive to wind until the fuel has had at least one day of drying.

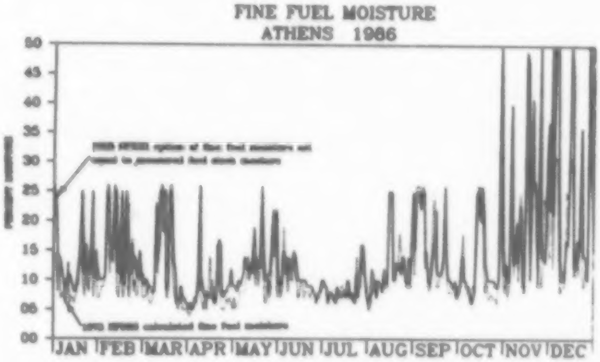


FIG. 5.--Measured fuel stick moistures are typically higher than calculated values, except during the driest periods. They also show greater response to rainfall events.

OVERRATING AUTUMN FIRE DANGER

A primary reason the 1978 NFDRS overrated autumn fire danger is its poor ability to simulate fall curing. Herbs and shrubs may freeze at different times, and the shrubs may be deciduous. Neither of these circumstances can be addressed within the 1978 NFDRS. Also, because the vegetation is assumed to cure immediately when a freeze occurs, the result can be an instantaneous increase in fire danger. The greenness factors in the revised system permit simulation of gradual fall curing, resulting in a gradual increase of autumn fire danger.

In addition, the user can now define the live woody fuel load as deciduous or evergreen. Deciduous models allow simulation of leaf fall by permitting load transfers between the live woody class and the fine dead fuel class, as a function of the live woody greenness factor. Figure 6 compares live woody fuel load profiles for the 1978 NFDRS and the 1988 revision with the deciduous option selected.

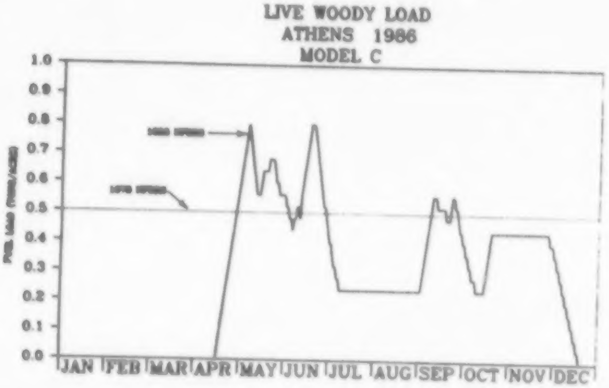


FIG. 6.--Live woody fuel load profile comparison for the 1978 and 1988 NFDRS, during a drought year in the Southeastern United States. The deciduous option was chosen for the live woody fuel load.

The 1988 NFDRS also provides a variable windspeed adjustment factor for fuel types that have a deciduous live woody fuel load (Figure 7). The windspeed is reduced most whenever the shrubs are fully green, and least when the shrubs have lost their leaves. These conditions are indicated by user entry of the live woody greenness factor. The windspeed adjustment remains constant for fuel models whose live woody load is declared to be evergreen.

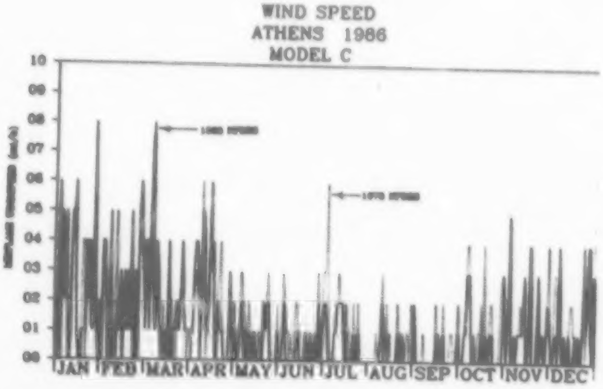


FIG. 7.--The variable wind adjustment factor of the 1988 NFDRS can produce higher calculated mid-flame windspeeds during the winter, but lower mid-flame windspeeds during the summer, than does the 1978 NFDRS.

1988 NFDR FUEL MODELS

The changes described required modification of all 20 1978 NFDRS fuel models, so a second set of 20 fuel models was created. In some cases fuel loads were changed to improve the seasonal response, but the major changes involved adding minimum and maximum wind adjustment factors and a reservoir of dead fuel to improve the drought response. The user can choose either the original 1978 NFDRS fuel models or the 1988 revised models (Table 1, 2). Choice of the 1978 NFDR fuel models disables most of the 1988 revisions.

Results

The results of these changes can perhaps be best illustrated by looking at Spread Component, Energy Release Component, and Burning Index comparisons for the Athens, Georgia, data. For this example, fine dead fuel moisture was set equal to the fuel stick moisture and the live woody fuel was declared deciduous.

Because the Spread Component is strongly affected by fine dead fuel moisture, the effect is to produce a general reduction in the Spread Component throughout the year, with the effect being greatest during the cool, moist period of winter and early spring (figure 8). During the May-June period, the 1988 system Spread Component is near 0 for the additional reason that the 20-foot windspeeds are reduced most when the vegetation is in full leaf. A small effect of drought can be seen during the July-August and October periods when deep drying increased the amount of available fuel.

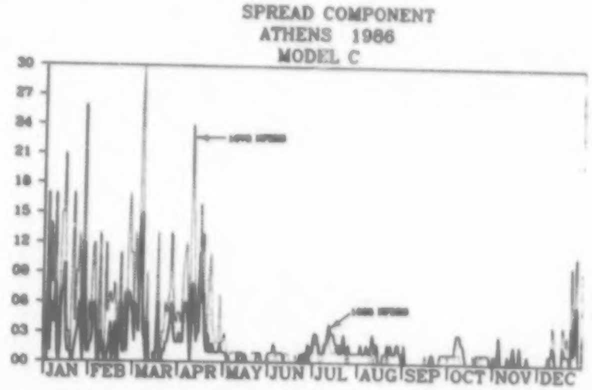


FIG. 8.--Setting the fine dead fuel moisture equal to the 10-hour timelag fuel moisture reduced the Spread Component during the relative moist winter and early spring period.

The Energy Release Component (figure 9) is slightly higher for the 1988 NFDRS than the 1978 NFDRS during the spring because the live woody load was designated to be deciduous, and was thus transferred to the fine dead fuel class during the dormant season.

Table 2.--1988 NFDRS fuel model descriptions

Fuel model parameters	Fuel model																			
	A	B	C	D	E	F	G	H	I	J	K	L	N	O	P	Q	R	S	T	U
Load (tons/acre)																				
1-hour dead	0.2	3.5	0.4	2.0	1.0	2.5	2.5	1.5	12.0	7.0	2.5	0.25	1.5	2.0	1.0	2.5	0.5	0.5	1.0	1.5
10-hour dead	--	4.0	1.0	1.0	0.5	2.0	2.0	1.0	12.0	7.0	2.5	--	1.5	3.0	1.0	5.4	0.5	0.5	0.5	1.5
100-hour dead	--	0.5	--	--	0.25	1.5	5.0	2.0	10.0	6.0	2.0	--	--	3.0	0.5	2.9	0.5	0.5	--	1.0
1000-hour dead	--	--	--	--	--	--	12.0	2.0	12.0	5.5	2.5	--	--	2.0	--	1.0	--	0.5	--	--
Woody	--	11.5	0.8	3.0	1.0	7.0	0.5	0.5	--	--	--	--	2.0	7.0	0.5	3.0	0.5	0.5	2.5	0.5
Herbaceous	0.3	--	0.8	1.0	0.5	1.0	0.5	0.5	--	--	--	0.5	--	--	0.5	1.0	0.5	0.5	0.5	0.5
Drought	0.2	3.5	1.8	1.5	1.5	2.5	5.0	2.0	12.0	7.0	2.5	0.25	2.0	3.5	1.0	3.5	0.5	1.5	1.0	2.0
Surface-area-to-volume ratio (1/ft)																				
1-hour dead	3,000	700	2,000	1,250	2,000	700	2,000	2,000	1,500	1,500	1,500	2,000	1,600	1,500	1,750	3,500	1,500	1,500	2,500	1,750
10-hour dead	--	109	109	109	109	109	109	109	109	109	109	--	109	109	109	109	109	109	109	109
100-hour dead	--	30	30	--	30	30	30	30	30	30	30	--	--	30	30	30	30	30	--	30
1000-hour dead	--	8	--	--	--	--	8	8	8	8	8	--	--	8	--	8	8	8	--	--
Woody	--	1,250	1,500	1,500	1,500	1,250	1,500	1,500	--	--	--	--	1,500	1,500	1,500	1,500	1,500	1,200	1,500	1,500
Herbaceous	3,000	--	2,500	1,500	2,000	1,500	2,000	2,000	--	--	--	2,000	--	1,500	2,000	1,500	2,000	1,500	2,000	2,000
Heat content (all fuels) (Btu/lb)	8,000	9,500	8,000	9,000	8,000	9,500	8,000	8,000	8,000	8,000	8,000	8,000	8,700	9,000	8,000	8,000	8,000	8,000	8,000	8,000
Moisture of extinction (%)																				
Dead	15	15	20	40	25	15	25	20	25	25	25	15	40	30	30	18	25	25	15	20
Fuel bed depth (ft)	0.8	4.5	0.25	2.0	0.4	4.5	1.0	0.3	2.0	1.3	0.6	1.0	3.0	4.0	0.4	2.0	0.25	0.4	1.25	0.5
Minimum wind adjustment factor	0.6	0.5	0.3	0.4	0.3	0.5	0.3	0.3	0.5	0.5	0.5	0.5	0.5	0.5	0.3	0.2	0.3	0.6	0.6	0.3
Maximum wind adjustment factor	0.6	0.5	0.5	0.4	0.5	0.5	0.3	0.3	0.5	0.5	0.5	0.5	0.5	0.5	0.3	0.3	0.5	0.6	0.6	0.3
SC_{max}	301	58	32	68	25	24	30	8	65	44	23	178	167	99	14	59	6	17	96	16

The most dramatic difference, however, occurs during the summer drought, when the Energy Release Component is significantly increased due to the addition of drought fuel to simulate deep drying, and to the coincidental reduction of live fuel moistures through reduction of the greenness factors.

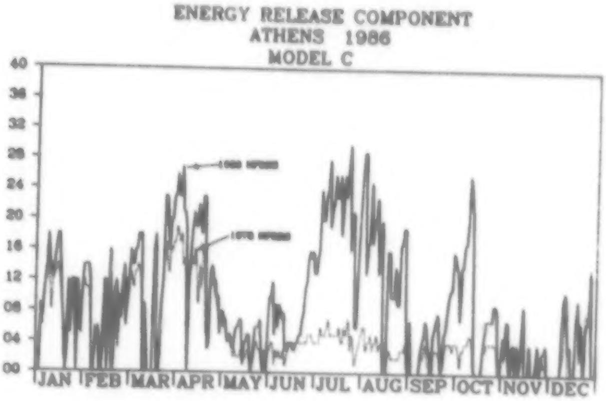


FIG. 9.--The Energy Release Component strongly reflects the effect of drought due to the dynamic dead fuel load and through reduction of calculated live fuel moisture.

The Burning Index is a function of both the Energy Release Component and the Spread Component, so it is most effective in illustrating the combined effects of all the System revisions (figure 10). Winter and early spring Burning Index values are reduced primarily by letting fine dead fuel moisture equal measured fuel- stick moisture. Summer drought is better reflected through a combination of increased dead fuel availability and reduced live fuel moisture. The Burning Index increase is slower in late November and December, as a result of a more gradual simulation of the fall curing process.

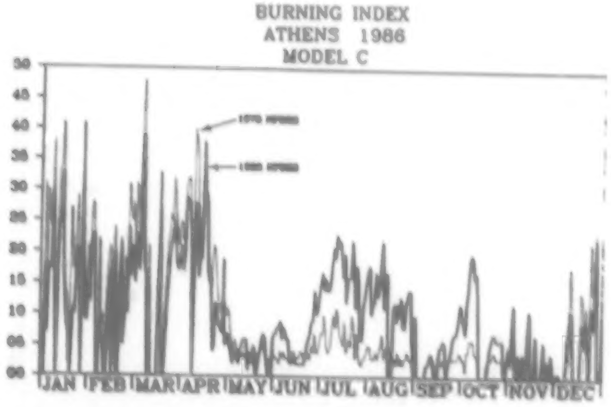


FIG. 10.--The Burning Index effectively illustrates the combined effects of the system revisions.

Operational Considerations

These revisions have been structured to enable fire managers to use the System nearly unchanged, or to select those modifications that address specific local problems. The exceptions are mandatory daily entry of greenness factors for live herbaceous and woody fuels, and precipitation amount which is used in calculating the Keetch-Byram Drought Index. In addition, average annual precipitation has to be added to the station catalog.

The user has three options for implementing the 1988 NFDRS:

- Choice of the 1978 or the 1988 NFDRS fuel model set.
- Whether or not to set the fine dead fuel moisture equal to 10-hour moisture.
- Whether to define the live woody vegetation as deciduous or evergreen.

The 1988 NFDRS revisions have been structured so the options can be selected in a manner that will minimize impacts on users who were not seeking system changes, yet allow eastern users to select options that permit them to deal effectively with their concerns. In all cases, however, proper weather station location and maintenance as well as consistent and accurate weather observations and entries are critical. The National Fire Danger Rating System has always required entry of weather data EVERY day. This revision does nothing to change that. The revised fire danger rating system is now fully implemented nationally through the AFFIRMS and FIRDAT programs, and through a personal computer version of the system.

Full documentation of the 1988 revisions to the 1978 National Fire Danger Rating System can be obtained by ordering the parent publication, "1988 Revisions to the 1978 National Fire Danger Rating System" (Burgan 1988) from the Southeastern Forest Experiment Station, P. O. Box 2680, Asheville, NC
28802.

References

ANDERSON, H. E. 1985. Moisture and fine forest fuel response. P. 192-199 In L. R. Donoghue and R. E. Martin, eds., Proc. Eighth Conf. Fire and For. Meteor., Detroit, Mi., Apr. 29 - May 3, 1985, Soc. Amer. For., Bethesda, Md., SAF Publ. 85-04.

BURGAN, R. E. 1988. 1988 Revisions to the 1978 National Fire Danger Rating System. USDA For. Serv. Res. Paper SE-273, Southeastern For. Exp. Sta.

DEEMING, J. E., R. E. BURGAN, AND J. D. COHEN. 1977. The National Fire-Danger Rating System--1978. USDA For. Serv. Gen. Tech. Rep. INT-39, Intermountain For. and Range Exp. Sta.

KEETCH, J. J., AND G. M. BYRAM. 1968. A drought index for forest fire control. USDA For. Serv. Res. Pap. SE-38, Southeastern For. Exp. Sta.

Smoldering Combustion Limits in Peat as Influenced by Moisture, Mineral Content, and Organic Bulk Density

R.A. HARTFORD
Intermountain Research Station,
Forest Service, U.S. Department of Agriculture
Missoula, Montana.

Abstract

The occurrence of smoldering ground fire in organic soils and organic horizons can be predicted based on moisture content. However, the limits of smoldering combustion in organic matter are also affected by the amount and type of incorporated mineral soil and the compaction of the fuel bed.

Peat moss was conditioned through a range of moisture contents from oven dry to greater than 120 % on an oven dry, mineral free basis. It was mixed with mineral soil to represent a range of mineral contents from the inherent mineral in peat through the mineral contents seen in upper mineral soil horizons. The mineral soil, sifted to finer than 240 mesh, was from one of three sources: an illitic silty clay, an ashcap soil (allophane clay), and powdered silica. The mixture was then packed in an insulated test box to one of three organic bulk densities representing the range encountered commonly in the field. The fuel was ignited, then observed for self-sustained combustion.

Logistic regression analysis was used to develop classification equations from the burn/no-burn data. These equations can be used to predict whether organic matter will support smoldering combustion following ignition.

Résumé

La fréquence de feux couvants dans des sols et des horizons organiques peut être prédite à partir de la teneur en humidité. Les limites de la combustion couvante dans la matière organique peuvent toutefois être affectées par la quantité et le type de sol minéral incorporé et le degré de compactage du lit de combustibles.

On a traité de la tourbe de mousse pour lui donner diverses teneurs en humidité, allant d'un état anhydre à plus de 120% séchée à l'étuve, sans sol minéral. Elle a ensuite été mélangée à du sol minéral pour obtenir une gamme de teneurs en sol minéral allant de la valeur intrinsèque de matières minérales dans la tourbe aux valeurs observées dans les horizons supérieurs du sol minéral. Le sol minéral, passé dans un tamis de plus de 240 mailles, provenant d'une de trois origines: argile limoneuse illitique, sol cinéritique (argile allophane) et silice pulvérisée. Le mélange a ensuite été tassé dans une boîte isolée d'essai pour obtenir l'une des trois densités organiques apparentes qui représente la variation couramment observée sur le terrain. La matière combustible a été enflammée pour observer la soutenance autonome de la combustion.

Une analyse de régression logistique a été utilisée pour élaborer des équations de classification à partir des données de consumation/non consumation. Ces équations peuvent servir à prédire si la matière organique donnera lieu à une combustion couvante après l'inflammation.

Introduction

The decomposing vegetative matter that makes up the forest floor is one of many strata of fuel that may be affected by or involved in fire. Whether that involvement is as a heat absorber or as a heat source will have a bearing on the biological and physical effects of fire on a site. There are prediction equations of the extent of duff consumption or duff reduction such as the recent work of Brown et al. (1985) and Little et al. (1986). However, the behavior of ground fire has not been thoroughly described.

The burning characteristics of duff need to be determined and described to better understand fire effects. Frandsen (1987) discussed the influence of both moisture and inorganic content as factors controlling the combustion limits in duff. The objectives of the study described in this paper were to further investigate the effects of moisture content and inorganic content on the limits of self-sustained smoldering combustion, smoldering that continues without the presence of an additional heat source, by altering soil type and the density of the organic material.

The probability that peat will burn once ignited can be estimated from moisture content, inorganic content, and bulk density. The likelihood that smoldering will be sustained decreases as any of these variables increases. The probability of sustained smoldering varies depending on the source of the inorganic component and physical characteristics of the peat.

The forest floor is a highly variable fuel source. Duff depths and moisture content show wide spatial and temporal variability throughout forest stands (Potts et al. 1983). Characteristics such as particle size, shape, bulk density, and mineral content also vary widely with

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

depth of duff at any one location. Mineral soil may become incorporated in organic horizons as a result of freeze/thaw processes, insect and small animal activity, overland flow, wind throw, or managment activities. inorganic content of organic horizons tends to increase with increasing depth in the organic layer.

Soil chemical and physical characteristics may influence smoldering. Allophane clays (such as the amorphous silicate mineral in soils developed from volcanic ash) and crystal lattice clays tend to be hygroscopic, adsorbing water on their surface (Brady 1984), which would be released within the fuel bed upon the approach of the smoldering front. Lattice clays release additional water that is bound in the lattice structure as the soil is heated above 500° to 600°C (Mitra et al. 1985). Both allophane and lattice clay soils tend to have high capacity to adsorb cations. Allophane clays also have a significant capacity to adsorb anions. The presence of cations such as calcium and magnesium are known to accelerate smoldering. Manganese and iron in trace amounts can enhance smoldering while some anions inhibit smoldering (Nevell and Zeronian 1985).

Methods

Peat was used in this study because it is an organic soil similar to forest duff but far more uniform in the physical and chemical characteristics that could influence fire behavior. Finely ground silica was used as a "standard" for comparison because it does not have associated cations and it is not hygroscopic.

Peat was conditioned to specified moisture content by adding water to containers of peat, mixing thoroughly, sealing the container, and allowing the mixture to come to equilibrium. Percentage moisture content was determined with a thermogravimetric moisture analyser. Inherent mineral content of the peat was determined by mass remaining after ignition. Soils were sieved to finer than 240 mesh to facilitate uniform mixing and stored at an oven dry moisture content.

Moisture and inorganic proportions were reported on a ratio basis. The moisture ratio is the ratio of the mass of water to the mass of dry, mineral-free organic material. The inorganic ratio is the mass of dry inorganics of added soil, plus the dry mass of the inherent mineral in the peat, to the dry mass of mineral-free organics. The organic concentration is the mass of dry, mineral free organic matter per unit volume. It is the bulk density of the organic material in the bed.

The study was divided into two phases. In phase 1, the inorganic fraction was one of three soil types: silica, obtained as a pure chemical, an illitic clay from lacustrine deposits, and an allophane clay of an andept or ash soil. The organic concentration was held constant at 0.11 g/cc. In phase 2, silica was the source of added inorganics for all tests, which encompassed three levels of organic concentration: 0.07, 0.11, and 0.17 g/cc. These densities represent the minimum, the mean, and common high values of data on file at the Intermountain Fire Sciences Laboratory (IFSL) as sampled in the lower duff of several forest types in western Montana. Phase 1 was completed with Green Thumb[1] brand peat, which had a high content of fine fibrous material and a low inherent mineral content averaging 4%, based on the dry weight of the peat. In phase 2, Sunshine brand peat was used that, though from the same bog, had been mined from a more humified area. It had fewer long fibers, more fine particles and a mineral content of 8%. A comparison of the data from tests at .11 g/cc organic concentrations, with silica as the inorganic source, from each phase was used to determine the difference in the smoldering combustion limits that might be attributed to peat particle characteristics. The moisture ratio ranged from 0.0 (oven dry) through 1.2. The inorganic ratio ranged from the inherent mineral content of the peat through 5.4.

Fuel beds were prepared with moisture conditioned peat to which mineral soil was added to the specified inorganic ratio and thoroughly mixed. This mixture was packed to a depth of 4 cm in a randomly assigned, open topped, insulated box. The thermal properties of the insulating material were sufficiently similar to the peat as to prevent the appearance of an edge effect at the peat/insulation interface. This allowed tests to be conducted in a small box (about 9 X 9 cm in base area), which is adequate considering the slow rate of burning by the smoldering process. The fuel bed was ignited by a glowing resistance coil placed 1 to 2 mm from the fuel surface and left in position for 3 minutes. All beds were ignited then observed to determine if smoldering combustion would continue after ignition, unaided by additional surface heating.

Burn tests were conducted in the laboratory at ambient room temperatures and relative humidities (19° to 23°C and 20% to 30% respectively) under fume hoods with adequate air flow to ventilate the smoke but not enhance the burn conditions.

Classification of results was clear cut. Cases were classified as "burn" if combustion continued until all available fuel was consumed. A "no burn" was as easy to determine. The ignition point appeared to be reduced to white ash and some charring appeared around the rim of the ignition point, but little of the available fuel was consumed. Residue was weighed from over 400 tests. After accounting for the inorganics in the beds, less than 5% of the mass of the organics remained in the "burn" cases and over 95% of the organics remained in the "no burn" cases. Of the 691 individual burn tests, only three burned partially. These were classified with the "no burn" group. Because of the definite nature of the results, tests were not conducted at moisture and inorganic ratios well beyond the region of the combustion limit boundary.

Analysis

Figure 1 is a typical scatterplot of the data showing the range of tests conducted in the three soil types.

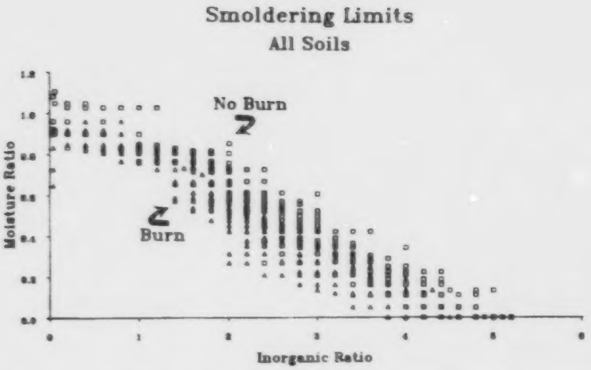


FIG 1. Combined scatterplot of moisture ratio versus inorganic ratio for combustion limits burn outcome in all soils. "Burn" outcome is indicated by a triangle, and "no burn" by a square.

There is a zone of uncertainty of burn outcome that includes both fires that continued to burn (triangles) and those that did not (squares). This area represents a combustion limit boundary. Above this zone the likelihood of sustained burning is 0%. Below, the likelihood of sustained burning is 100%.

Because of the dichotomous nature of the dependent variable ("burn" = 1 and "no burn" = 0), logistic regression analysis was used to develop predictive equations of the probability that a fuel bed would burn based on the values of the independent variables being tested. This analysis was conducted using the CATMOD procedure of the SAS System.

Goodness-of-fit was tested by grouping the data based on the predicted probability of burning in 10 categories from 0.0 to 1.0 by 0.1. A Chi-square statistic with 8 degrees of freedom could then be calculated for each model. Grouping and testing the data in this way also allowed examination of regions of poor predictive ability.

Results and Discussion

In phase 1, logistic regression analysis indicated that silica and clay soil inorganics did not cause significantly different results. Ash soil, however, did appear to be a significant variable. The data were split to one group containing tests with silica or clay soil and another containing only tests with ash soil. Once separated, logistic equations were developed for each group.

$$\hat{P} = 1/(1 + e^{-21.470 + (21.114)R_M + (4.5701)R_I})$$

for fuel beds including silica or clay soils

$$\hat{P} = 1/(1 + e^{-16.671 + (15.407)R_M + (3.9981)R_I})$$

for fuel beds including ash soils

Where: $\hat{P}$ = probability of burning
R_M = the moisture ratio
R_I = the inorganic ratio

Figure 2 shows the probability of burning for the two soil classes, silica/clay and ash soil, at 0.2, 0.4, 0.6, and 0.8 moisture ratios. Note that at high moisture ratio, the probability of burning is higher with ash soil than with silica/clay while at low moisture ratios the probability of burning is lower with ash soil.

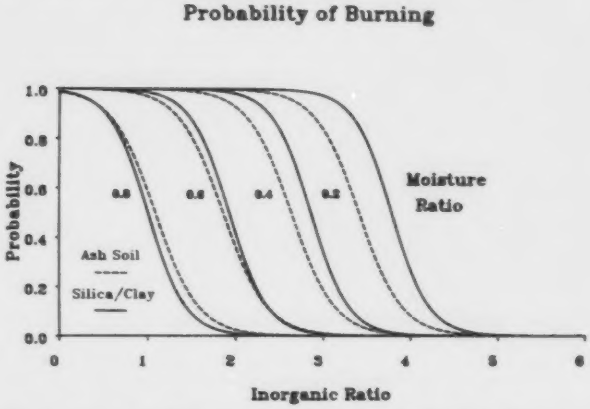


FIG 2. The probability of sustained smoldering combustion in peat versus inorganic ratio by 0.2 moisture ratio intervals.

In phase 2, the test of the effect of density on combustion limits, the organic concentration was determined to be a significant independent variable. The best fitting equation included organic concentration as an interaction term expressed by the bulk density of the dry fuel bed.

$$\rho_B = \rho_O (R_I + 1) \qquad (3)$$

Where:

ρ_B = the bulk density of the bed
ρ_O = the organic concentration
ρ_O * R_I = the inorganic concentration

Then:

$$\hat{P} = 1/(1 + e^{-19.329 + (17.047)R_M + (1.7170)R_I + (23.059)\rho_B})$$

Figure 3 shows the probability of burning at three organic concentrations of 0.17, 0.11, and 0.07 g/cc at the moisture ratios of 0.2 and 0.8. Decreasing the density of the bed increases the probability of sustained smoldering. This effect is most pronounced at low moisture ratios.

Table 1 is an analysis of the fit of these equations. Comparison of the number of observed and expected burn outcomes at probability class groups allows interpretation of the fit of the equation through the

Table 1. Analysis of logistic equations: observed and expected outcome grouped by 0.1 probability categories.

a. silica/clay soil

P	Total Burns	"Burn"		"No burn"	
		0	E	O	E
0-.1	50	3	2.3	47	47.7
.1-.2	41	3	6.3	38	34.7
.2-.3	35	11	8.5	24	26.5
.3-.4	30	11	10.7	19	19.3
.4-.5	18	9	8.1	9	9.9
.5-.6	21	11	11.9	10	9.1
.6-.7	28	19	17.9	9	10.1
.7-.8	29	21	21.9	8	7.1
.8-.9	31	25	26.4	6	4.6
.9-1.0	39	38	36.9	1	2.1
	322	151		171	

$X^2 = 5.01$
d.f. = 8

P-value = .757

b. Phase 1, ash soil

P	Total Burns	"Burn"		"No burn"	
		0	E	O	E
0-.1	19	0	1.0	19	18.0
.1-.2	20	3	3.0	17	17.0
.2-.3	17	5	4.4	12	12.6
.3-.4	8	3	2.8	5	5.2
.4-.5	16	5	7.1	11	8.9
.5-.6	9	6	4.9	3	4.1
.6-.7	17	14	11.0	3	6.0
.7-.8	14	11	10.5	3	3.5
.8-.9	19	16	16.1	3	2.9
.9-1.0	14	11	13.2	3	0.8
	153	74		79	

$X^2 = 12.02$
d.f. = 8

P-value = .151

c. Phase 2, density

P	Total Burns	"Burn"		"No burn"	
		0	E	O	E
0-.1	40	1	2.1	39	37.9
.1-.2	35	6	5.2	29	29.8
.2-.3	19	4	4.9	15	14.0
.3-.4	17	10	6.0	7	11.0
.4-.5	17	6	7.6	11	9.4
.5-.6	12	6	6.5	6	5.5
.6-.7	17	12	11.0	5	6.0
.7-.8	17	12	12.9	5	4.1
.8-.9	21	16	17.8	5	3.2
.9-1.0	21	21	19.9	0	1.1
	216	94		122	

$X^2 = 8.57$
d.f. = 8

P-value = .380

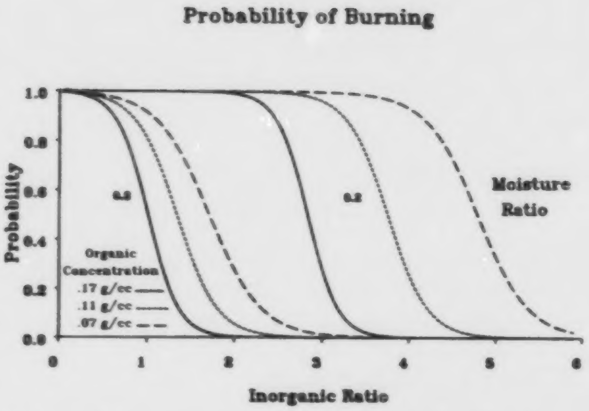


FIG 3. The probability of sustained smoldering combustion in peat versus inorganic ratio at 0.2 and 0.8 moisture ratio levels.

range of probability classes as well as analysis of the overall goodness-of-fit.

The final comparison was made between the two series of burns using silica and peat at an organic ratio of 0.11 g/cc in which the peat particle size distribution and particle shape were different. The purpose of this analysis was simply to determine if peat type was a significant factor in determining the probability of burning. This dummy variable was accepted with a probability value of 0.0001, indicating there are differences in the likelihood of burning due to some characteristic of the peat itself. The boundary region of the smoldering limit is shifted toward a lower moisture and lower inorganic level in the more humified peat. This has significance in relating the combustion limits in peat to the combustion limits in duff. Frandsen (1987) included a figure showing the similarity in shape of the boundary region of the combustion limits in peat and the limits in Douglas-fir duff that had been ground to a similar dimension as peat but lacking in the long fibrous component. A set of field burns conducted in a variety of forest cover types also indicated a combustion limit shifted toward lower moisture and lower inorganic ratios (data on file at IFSL) but with a combustion limit region similar in shape to those of peat burns.

Summary

The probability that peat will burn once ignited can be estimated based on knowledge of the moisture content, inorganic content, and the bulk density. As the value of any of these increases, the likelihood that smoldering combustion will be sustained is decreased.

Organic matter in which ash soils have been mixed burn somewhat differently than beds incorporating other soils. However, this may be of more curious than practical value because the boundary region of uncertainty of outcome is broad due to the wide spatial variability that is seen in moisture and inorganic content on field sites. Further research is needed to study the effects of particle dimension and chemical composition, as related to degree of decomposition, on smoldering combustion limits.

Endnotes

[1] The use of trade or firm names in this paper is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

References

BRADY, N. C. 1984. The nature and properties of soil. 9th ed. The Macmillan Publishing Co., New York. p. 424.

BROWN, J. K., M. A. MARSDEN, K. C. RYAN, and E. D. REINHARDT. 1985. Predicting duff and woody fuel consumed by prescribed fire in the Northern Rocky Mountains. USDA For. Serv. Res. Pap. INT-337. Intermountain Res. Sta.

FRANSDEN, W. H. 1987. The influence of moisture and mineral soil on the combustion limits of smoldering forest duff. Can. J. For. Res. 17:1540-1544.

LITTLE, S. N., R. D. OTTMAR, and J. L. OHMANN. 1986. Predicting duff consumption from prescribed burns on conifer clearcuts in western Oregon and western Washington. USDA For. Serv. Res. Pap. PNW-362. Pacific NW Exp. Sta.

MITRA, N. K., D. DAS., A. SEN, and A. BASUMAJUMDAR, A. 1985. Influence of exchangeable cations on DTA characteristics of kaolinite and montmorillonite clays. J. Indian Chem Soc. 92(9):662-665.

NEVELL, T. P., and S. H. ZERONIAN. 1985. Cellulose chemistry and its applications. John Wiley & Sons, New York.

POTTS, D.F., H. ZUURING, and M. HILLHOUSE. 1983. Spatial analysis of duff moisture and structure variablility. P. 18-21 In Proceedings of the 7th Conference on Fire and Forest Meteorology. Ft. Collins, CO. American Meteorological Society, Boston, MA.

Predicted vs Observed Fire Spread Rates in Ponderosa Pine Fuel Beds: A Test of American and Canadian Systems

R.S. MCALPINE
Forestry Canada
Edmonton, Alberta

G. XANTHOPOULOS
University of Montana
Missoula, Montana

Abstract

The Canadian Forest Fire Behavior Predic[illegible]P) System and the American BEHAVE fire behavior prediction system differ in many respects. These diss[illegible]ies stem from a basic difference in the two approaches of the fire behavior prediction problem; the Canadians used an empirical approach in system design, while the Americans developed an adaptable theoretical model. In the spring of 1988 a series of 17 experimental fires in ponderosa pine (Pinus ponderosa Laws.) needle litter were conducted in the wind tunnel combustion facilities of the Intermountain Fire Sciences Laboratory in Missoula, Montana. The fires were part of investigations into crown fire initiation, and fire acceleration from a point source. However, the data collected allowed the observed equilibrium head fire rate of spread (ROS) to be compared to estimates computed by both the American and Canadian fire behavior prediction systems. The American BEHAVE system tended to underpredict observed ROS by 15-60 %, possibly due to wind speed profiles differing from the original developmental study or inaccurate estimation of moisture of extinction. The Canadian FBP System tended to overpredict observed ROS, due in part to problems in computing a 10-m open wind speed equivalent to the wind tunnel (midflame) wind speed.

Résumé

La Méthode canadienne de prévision du comportement des incendies de forêt et le système américain de prévision du comportement du feu BEHAVE sont différents à plusieurs égards. Ces dissimilitudes sont attribuables à une différence fondamentale des deux approches au problème de prévision du comportement du feu; les canadiens ont utilisés une approche empirique dans l'élaboration du système tandis que les américains ont élaborés un modèle théorique adaptable. Au printemps 1988, une série de 17 feux expérimentaux de litière d'aiguilles de pin ponderosa (Pinus ponderosa Laws.) a été menée aux installations de combustion avec soufflerie de l'Intermountain Fire Sciences Laboratory de Missoula au Montana. Ces essais étaient menés dans le cadre de deux projets de recherche, l'un sur la naissance de feux de cime et l'autre sur l'accélération du feu à partir d'une source ponctuelle. Les données ont toutefois permis que la vitesse observée de propagation (VDP) d'équilibre du feu soit comparée aux estimations calculées par les systèmes canadiens et américains de prévision du comportement du feu. Le système américain BEHAVE avait tendance à sous-prédire la VDP observée par 15-60%, possiblement à cause du profil de la vitesse des vents qui était différent de l'étude originale élasorée ou l'estimation inexacte de l'extinction de l'humidité. La Méthode canadienne de prévision du comportemant des incendies de forêt avait tendance à sur-prédire la VDP observée, en pantie à cause de problémes encourus lors du calcul de l'équivalent de lavitesse en plein vent de 10m à la vitesse du vent (mi-flamme) dans la soufflerie.

Introduction

During the spring of 1988, as part of a study on the acceleration of point source fires, a total of 29 experimental fires (17 of which were in ponderosa pine (Pinus ponderosa Laws.) needle litter fuel beds) were conducted in the wind tunnel burning facilities of the Intermountain Fire Sciences Laboratory in Missoula, Montana. Following completion of the burning it was thought that the observed equilibrium spread rates might be compared to a predicted rate of spread from the U.S. BEHAVE fire behavior prediction system. Additionally, although the Canadian Forest Fire Behavior Prediction (FBP) System is based on field research data, it was thought that it might be interesting to attempt a prediction, given the laboratory conditions.

All fire behavior prediction systems attempt to predict wildland fire behavior based on certain key elements of the fuel and concurrent weather conditions. These key elements vary from system to system but always include a fuel type characterization (or classification), fuel moisture content (FMC), wind speed, and topographic slope. The "proof of the pudding" of any behavior prediction system is not in the ease of use, versatility, or basis for derivation; it is how well the fire behavior prediction matches observed wildland fire behavior. While the burning of fuel beds in a

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

wind tunnel cannot be considered the equivalent of a wildland fire, the results proved to be interesting.

Each fire behavior prediction system has its strengths and weaknesses. The original philosophy and derivation of each system influence how well it will work under a variety of fuel and weather conditions. The U.S. system is based on physical heat transfer theory and a series of laboratory fires. The Canadian system is based largely on field experimental fires (with wildfire data used when available) tempered with physical theory. The advantages of both research approaches are discussed elsewhere (Van Wagner 1971, Catchpole and de Mestre 1986). The differing approach to research in the two countries is likely a product of the personnel responsible for the research; the U.S. researchers are largely engineers, physisists, and mathematicians, while in Canada foresters are the primary researchers. A general description of each system should elucidate the differences.

U.S. BEHAVE

BEHAVE is an interactive computer-based fire behavior prediction and fuel modelling system developed by United States Department of Agriculture personnel at the Intermountain Fire Sciences Laboratory in Missoula, Montana. BEHAVE has been an approved U.S. national fire behavior prediction system since 1984 and is currently used in a variety of fire management applications.

BEHAVE is divided into two subsystems: FUEL (Burgan and Rothermel 1984) for fuel modelling and BURN (Andrews 1986) for operational fire behavior prediction. The objective of fuel modelling is to describe vegetation in terms that can be used in the mathematical prediction model (Rothermel 1972). Each subsystem consists of two parts: knowledge base and control (Andrews and Latham 1984). The knowledge base, which is the key component of the system, consists of mathematical models, heuristics, and fuel models. The control structure mainly facilitates the interaction between the user and the knowledge base and controls the flow of the program.

Rothermel's (1972) mathematical fire spread prediction model is the core of the fire behavior prediction capability of the BURN subsystem. The mathematical fire spread model uses wind speed, slope, fuel moisture and a fuel model to predict the rate of spread (ROS) and intensity of a fire. A fuel model is defined as a simulated fuel complex for which all the fuel descriptors required for the solution of the mathematical fire spread model have been specified. Other models in the BURN subsystem predict flame length, fire area and perimeter, spotting distance, suppression force capabilities, moisture content of fine dead fuels, wind speed adjustment factor, and curing of live fuel (Andrews 1986). Rate of spread estimation which is the focus of this study, is mainly based on the mathematical fire spread model, so the comparisons made here mainly apply to this model.

Rothermel's (1972) mathematical fire spread model was designed on the conservation of energy principle. Equilibrium ROS is the ratio between the heat flux received from the advancing flames (heat source) and the heat required for ignition by the potential fuel (heat sink). By breaking up the problem in this way Rothermel was able to quantify separately the factors affecting the heat source and the heat sink, examining each term either experimentally or analytically. The resulting model is completely different from older systems, which were mainly based on empirical relationships between burning conditions and broad fuel types. This model not only predicts ROS based on burning conditions but allows the user to describe the fuel in detail based on a number of standard fuel measurements. As a result, site-specific fuel models can be created. Thirteen stylized fuel models representative of common fuel complexes in the U.S. are in use with this system (Anderson 1982). The user can choose to use these discrete models, modify them, or create site specific fuel models if additional fuel data are available. The FUEL subsystem in BEHAVE also provides weighting procedures for inclusion of more than one fuel stratum in the description of a fuel complex.

The Rothermel fire spread model (and hence BEHAVE) is intended to describe a flame front advancing steadily in surface fuels within 2 metres of, and contiguous to, the ground; severe fire behavior (crowning, spotting, etc.) is not predicted by the model (Rothermel 1983).

The inputs required by the mathematical model for head fire ROS prediction are (Rothermel 1972):

1. ovendry fuel loading (kg/m^2),
2. fuel depth (m),
3. fuel particle surface area to volume ratio (cm^2/cm^3),
4. fuel particle low heat content (kJ/kg),
5. ovendry particle density (g/m^3),
6. fuel particle moisture content (fraction of ovendry weight),
7. fuel particle total mineral content (fraction of ovendry weight),
8. fuel particle effective mineral content ((grams silica - grams free minerals)/grams ovendry fuel),
9. wind velocity at midflame height (km/h),
10. site slope (vertical rise/horizontal run),
11. moisture content of extinction (fraction of ovendry weight).

Variables 5, 7, and 8 are held constant in the implementation of the model in BEHAVE because "they either have a small effect over their naturally occurring range or would be very difficult for the user to determine" (Burgan and Rothermel 1984). The value for moisture content of extinction in the model is difficult to obtain and requires experimental determination. Since moisture content of extinction is an influential variable, BEHAVE provides an estimation procedure (Burgan and Rothermel 1984).

THE CANADIAN FOREST FIRE BEHAVIOR PREDICTION (FBP) SYSTEM

The FBP System is a subsystem of the larger Canadian Forest Fire Danger Rating System (CFFDRS). The CFFDRS is an integrated modular forest fire danger rating system and, when complete, will consist of four modules or subsystems:

1) The Canadian Forest Fire Weather Index (FWI) System is composed of three fuel moisture codes and three relative fire behavior indexes (Canadian Forestry Service 1984). The codes and indexes are computed daily from noon temperature, relative humidity, wind speed, and 24-hr total rainfall measurements (Van Wagner 1987).

2) The Canadian Forest Fire Behavior Prediction (FBP) System is composed of four primary fire behavior outputs (head fire Rate of Spread (ROS), fuel consumption, frontal fire intensity, and type of fire) and three secondary fire growth measurements (forward spread distance, area burned, and perimeter length) (Alexander et al. 1984, Lawson et al. 1985) based on an elliptical fire growth model (Van Wagner 1969, Alexander 1985).

3) A proposed Fire Occurrence Prediction (FOP) System is envisioned as a single national framework consisting of both lightning and man-caused fire components (Stocks et al. 1988).

4) The incomplete Accessory Fuel Moisture System is a supplement to, or support of, special functions and requirements of the other three major systems. This system will include fuel specific moisture codes, corrections/adjustments for late starting fire weather stations, landform characteristics, latitude, season, time of day, and others (e.g., Van Wagner 1977).

Three factors played a prominent role in the maturation of the CFFDRS: 1) the development process was an evolution, where features were modified and retained from system to system during the 60+ years of development; 2) there is no direct fuel moisture content (FMC) evaluation (rather fire danger is calculated from direct fire weather observations); and 3) the underlying philosophy was to base the fire danger ratings on field experiments analyzed by empirical methods. This philosophy reflects the long established Canadian approach to fire behavior research: field documentation of readily measured variables on experimental fires (e.g., Alexander et al. 1984, Stocks et al. 1988) followed by analysis of the data using simple mathematical models and correlation techniques (Van Wagner 1971). Well-documented operational prescribed fires and wildfires have been used as well for system development, the latter being particularly useful to quantify the extreme end of the fire behavior scale. Laboratory-based fire research in moisture physics and heat transfer theory provides the models and framework by which field data are analyzed and explained. Because of the empirical nature of the data, phenomena not readily quantified by current physical models are automatically accounted for (e.g., the transition between surface and crown fire).

LABORATORY EXPERIMENTAL FIRES

The series of 17 experimental fires were conducted in the wind tunnel burning facilities of the Intermountain Fire Sciences Laboratory (ISFL), in Missoula, Montana. The experimental burning facilities are environmentally controlled and include two wind tunnels and a large combustion table (see Rothermel and Anderson 1966, Rothermel 1967).

During this experiment, temperature and relative humidity were held at a constant 26.7°C and 20 % throughout the burns. The moisture content of the fuel was not specifically controlled; rather, the fuel was allowed to come into equilibrium with the lab environment before burning, producing a fairly consistent fuel moisture content (FMC) for all burns (mean 8.6 %). Thus the fuel moisture functions of the two systems are not being tested. Four wind speeds were tested (0.0, 1.6, 4.8, and 8.0 km/h) covering the range of the wind tunnel's capability.

Fuel beds measured 0.915 m by 6.15 m and were composed of recently cast, cleaned ponderosa pine needles packed to a depth of 7.6 cm. Fuel beds were loaded to bulk densities of either 26.3 kg/m^3 or 13.12 kg/m^3 and packed according to procedures outlined in Schuette (1965). Fuel beds loaded to 26.3 kg/m^3 were burned at all wind speeds with a minimum of three replications (at the wind speed of 4.8 km/h five replications were done). The fuel beds loaded to 13.12 kg/m^3 were burned at one wind speed (4.8 km/h), with three replications.

For burning, the fuel beds were placed on the floor of the wind tunnel and ignited 1.2 m downwind of the front of the bed with a point ignition device. Head fire ROS was determined by regression analysis of the spread distance/elapsed time measurements, using only the measurements taken after the head fire had spread 2.0 m to allow for the period of acceleration to an equilibrium spread rate. Table 1 lists the fires conducted, environmental conditions, measured fuel moisture, and observed equilibrium ROS for each fire.

For more-complete information on the experimental design, documentation equipment, burning procedures, and results consult McAlpine (1988).

Table 1. Summary of all burns.

Burn no.	Bulk Density (kg/m^3)	Wind speed (km/h)	Temp. (°C)	R.H. (%)	Fuel moist. (%)	Head fire[*] equil. ROS (m/min)
1	26.3	1.6	27.6	20.9	8.2	0.46
2	26.3	8.0	27.1	19.8	7.9	4.50
3	26.3	4.8	27.3	20.9	8.4	1.45
4	26.3	1.6	27.1	20.9	8.1	0.48
5	26.3	1.6	26.9	20.5	8.2	0.60
6	26.3	4.8	27.3	20.0	7.7	1.73
7	26.3	4.8	26.9	19.9	8.8	1.48
8	26.3	8.0	27.0	21.3	8.4	2.16
9	26.3	8.0	27.8	19.7	8.3	3.03
21	13.1	4.8	27.1	19.7	8.9	2.09
22	13.1	4.8	27.2	20.6	8.9	2.19
23	13.1	4.8	27.6	21.2	8.7	2.52
24	26.3	0.0	27.4	20.4	9.9	0.38
25	26.3	0.0	27.1	20.9	9.4	0.37
27	26.3	0.0	27.0	21.4	8.7	0.37
28	26.3	4.8	27.5	20.8	9.2	1.25
29	26.3	4.8	27.0	20.0	8.8	1.30

[*] Regression results using spread data from 2.0 to 4.95 m downwind of the ignition point.

Table 2. Rate of spread prediction results for the U.S. and Canadian fire behavior prediction systems.

Burn no.	Wind Speed (km/h)	FFMC[a]	ISI[b]	Canadian Predicted[1] ROS (m/min)	U.S. Predicted[1] ROS (m/min)	Observed head fire equil. ROS (m/min)
24	0.0	90.9	44.8	0.46 (+21)	0.21 (-45)	0.38
25	0.0	91.4	5.2	0.55 (+49)	0.22 (-41)	0.37
27	0.0	92.1	5.7	0.67 (+81)	0.22 (-41)	0.37
1	1.6	92.6	7.8	1.31 (+185)	0.39 (-15)	0.46
4	1.6	92.7	7.9	1.35 (+181)	0.39 (-19)	0.48
5	1.6	92.6	7.8	1.31 (+118)	0.39 (-35)	0.60
3	4.8	92.4	12.3	3.51 (+142)	0.96 (-34)	1.45
6	4.8	93.1	13.6	4.33 (+150)	1.01 (-42)	1.73
7	4.8	92.0	11.7	.13 (+111)	0.94 (-36)	1.48
28	4.8	91.6	11.1	2.78 (+122)	0.92 (-26)	1.25
29	4.8	92.0	11.7	3.13 (+141)	0.94 (-28)	1.30
21[2]	4.8	91.9	11.5	3.03 (+45)	1.30 (-38)	2.09
22[2]	4.8	91.9	11.5	3.03 (+38)	1.30 (-41)	2.19
23[2]	4.8	92.1	11.8	3.22 (+28)	1.31 (-48)	2.52
2	8.0	92.9	21.5	11.06 (+146)	1.81 (-60)	4.50
8	8.0	92.4	20.0	9.84 (+356)	1.75 (-19)	2.16
9	8.0	92.5	0.3	10.08 (+233)	1.76 (-42)	3.03

[1] Numbers in brackets indicate the percent deviation from the observed value [(predicted - observed)/observed].

[2] These three burns were conducted at the lower fuel bulk density of 13.1 kg/m^3.

[a] FFMC - Fine Fuel Moisture Code

[b] ISI - Initial Spread Index

Fitting the Fuel and "Weather" to a Model

U.S. BEHAVE

The basic characteristics of BEHAVE made the prediction of rate of spread for this particular single layer fuel type very easy. Required fuel and environmental inputs were all simply measured or found in the literature.

Ovendry fuel loading, fuel bed depth, and fuel moisture content were measured. Ponderosa pine needle surface area to volume ratio was obtained from Brown (1970) (57.6 cm^2/cm^3). Heat content was assigned a value of 16,628 kJ/kg, the same value used for all 13 stylized fuel models. Wind velocity was one of the controlled variables in the wind tunnel. Slope was equal to zero for all burns. Finally, the moisture content of extinction was estimated at 34.0% through BEHAVE. BEHAVE predictions for head fire ROS appear in Table 2.

CANADIAN FBP SYSTEM

The application of the Canadian FBP System to the fuel/weather conditions of this experiment is more difficult than application of BEHAVE simply because the Canadian FBP System was designed for field conditions, integrating multilayered fuel types automatically in specific, discrete fuel types. Five distinct steps were required for a ROS prediction with the Canadian FBP System: 1) choose one of the 14 discrete fuel types to represent the artificial ponderosa pine needle litter fuel beds used; 2) calculate the equivalent Fine Fuel Moisture Code (FFMC, a moisture code from the FWI System) value from the measured FMC; 3) determine the equivalent 10-m open wind speed from literature relationships of in-stand wind speed vs. 10-m open wind speed; 4) compute the Initial Spread Index (ISI, a relative fire behavior index from the FWI System) value from the calculated FFMC and estimated equivalent 10-m open wind speed; and 5) calculate the predicted head fire ROS from the fuel type and ISI.

Selection of one of the discrete fuel models from the FBP System required some consideration. The first thought was use the C-7 (ponderosa pine--Douglas-fir) fuel type, since the fuel was ponderosa pine needle litter. Closer inspection of the C-7 fuel type description given by Alexander et al. (1984) ("except within Douglas-fir thickets the forest floor is dominated by perennial grasses, herbs and scattered shrubs") established that it does not describe closely the exclusive needle litter fuel used. The description for fuel type C-6 (red pine plantation) from Alexander et al. (1984) while not the correct species of needle litter provided a closer estimation of the fuel in question:

> "This fuel type is characterized by pure plantations of red pine, fully stocked so that crowns are

> closed and no understorey or shrub layer is present. The forest floor is covered by needle litter with an underlying duff layer of up to 10 cm in depth. The rate of spread relationships accommodate three ranges in mean stand height: 1) from 4 to 9.9 m, 2) from 10 to 20 m, and 3) more than 20 m."

Fuel type C-6 requires an estimate of stand height for equation selection, however, because trees in our case had no effect on the spread rate in our artificial fuel bed (i.e., there was no chance of crowning) the maximum height (more than 20 m) was selected.

The FFMC is easily determined from the FMC by equations provided by Van Wagner (1987):

$$F = 59.5(250 - m)/(147.2 + m)$$

$$m = 147.2(101 - F)/(59.5 + F)$$

Where F = FFMC
m = FMC

The FMC varied from a low of 7.7 % to a high of 9.97 %, producing an FFMC range of 93.1 to 90.9 respectively. A list of computed FFMC values for each fire appears in Table 2.

A 10-m open wind speed equivalent to the wind speeds measured in the wind tunnel is the most difficult estimation required for this study, since it greatly influences the final predicted ROS. Models to predict "midflame" wind speed from measured wind speeds at 6.1 m (20 ft) include those by Albini and Baughman (1979), Baughman and Albini (1980), Bergen (1971), Cooper (1965), Fons (1940), and Van Wagner (1987). Correction factors to estimate the 10-m open wind speed cited in these publications range from a high of 8.33 to a low of 1.78. With this extreme variation cited in the available literature, a similarly wide range in 10-m open wind speed estimates is possible. To alleviate this problem, the original study of fire behavior in the C-6 fuel type was consulted to establish the actual measured relationship between the stand wind and 10-m open wind speed. During the original study of fire behavior in the C-6 fuel type, the 10-m open wind speed was about three times the concurrent stand wind speed.[1] This factor of three is lower than most models would predict and is undoubtably the weakest link in the prediction; nevertheless, it provides a starting point from which we can move forward and will be accounted for in the final analysis.

Once the FFMC and 10-m open wind speed equivalent have been computed, ISI calculation is a trivial matter using the standard equations for ISI given by Van Wagner (1987) (computed ISI values for each fire are listed in Table 2):

$$f(W) = e^{0.05039(W)}$$

$$f(F) = (91.9e^{-0.1386(m)})[1 + m^{5.31}/(4.93 \times 10^{7})]$$

$$R = 0.208 \times f(W) \times f(F)$$

Where W = 10-m open wind speed (km/h)
f(W) = Wind effect function
m = Fine fuel moisture content (%)
f(F) = Fine fuel moisture function
R = Initial Spread Index (ISI)

Predicted head fire ROS (shown for each fire in Table 2) is then established using the equations provided by Alexander et al. (1984):

$$ROS = 0.01544 \times ISI^{2.16} \qquad \text{(for ISI} \leq 18)$$

$$ROS = 30\ [1 - e^{-0.0440 \times (ISI-11)}] \qquad \text{(for ISI} > 18)$$

Where ROS = Head fire rate of spread (m/min)
ISI = Initial Spread Index

Discussion

The information in Table 2 shows that generally the U.S. BEHAVE system underpredicts the observed laboratory ROS, while the Canadian FBP System overpredicts. This is better displayed in Figures 1 and 2, showing the trends of the prediction systems over the range of spread rates observed. The reasons for the prediction errors for each behavior prediction system are intrinsic to the design and nature of the system.

U.S. BEHAVE:

The BEHAVE system underpredicted ROS significantly, although its predictions followed the observed trend of ROS changes with varying wind velocity. Underpredictions ranged from 15 to 60 %, which can be considered a reasonable magnitude of deviation. The scientists responsible for BEHAVE have quite often cautioned users that deviations of this magnitude may occasionally happen. Specifically, they have said that "although fires are represented by single points on the chart, it must be remembered that this is only an estimate of fire behavior and a circle would be a better representation of the uncertainty of the calculation" (Rothermel 1983). Large deviations should be mostly expected when the fuel model used (stylized or site specific) does not correctly represent the fuel complex. Adjustment methods for fuel inputs have been suggested and discussed in detail (Burgan and Rothermel 1984). On the other hand, most input variables in this case were measured with an accuracy that is much higher than is possible in the field. Since homogeneity of the fuel bed is not in question in this case and since the study took place in the same wind tunnel where most of the original data for the mathematical fire spread model were obtained, one has to be very careful in trying to explain the observed deviations.

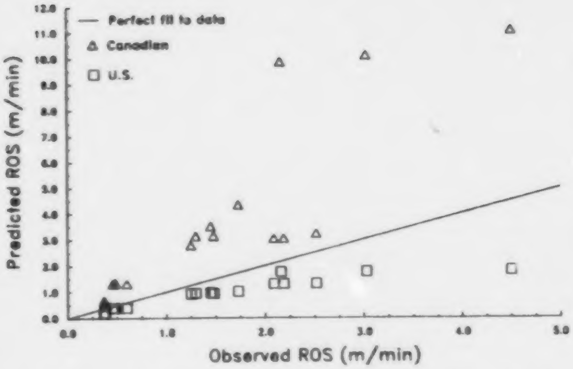


FIG 1. Comparison of observed and predicted head fire rate of spread values for both the Canadian FBP System and the U.S. BEHAVE System.

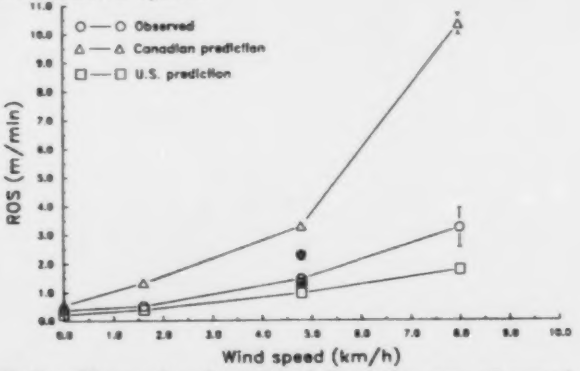


FIG 2. Observed and predicted head fire rate of spread measurments over the range of wind speeds tested. Filled symbols indicate lower fuel loading results. Average values for each set of conditions is shown, as well as standard error bars if discernible at the resolution displayed.

Two possible causes for the observed underpredictions have been identified. The first is the difference between the original wind tunnel study wind field and the one for the present study. Such differences in wind speed profiles can result in different boundary layer wind conditions. Rothermel and Anderson (1966) reported fire spread four to seven times faster in the first half of their initial test bed. When the laminar air flow of the wind tunnel was suddenly interrupted by the presence of the fuel bed, a tight rolling wind vortex was formed over the first 0.6 m of the bed. This phenomenon tipped the flames considerably further in that part of the fuel bed, resulting in more-efficient fuel preheating and consequently faster spread rates. The problem was solved by placing a 4-cm high trip fence (or spoiler) across the tunnel 0.30 m ahead of the fuel bed. This trip fence created a uniform turbulent boundary layer over the entire length of the fuel bed (Rothermel 1967). In the present study the trip fence was also utilized, but the wind profile over the fuel bed was not examined in detail. Differences in experimental design between the current study and the older study include fuel bed length (the current study fuel beds measured 6.15 m, while the original measured 3.66 m), fuel bed frames (different construction), fuel type (the current study used ponderosa pine needle litter, while the original study used excelsior and double tripod stick fuels), the addition of a wire mesh on the floor of the wind tunnel in advance of the fuel bed (to aid in the establishment of boundary layer wind conditions), and ignition technique (the current study used a point ignition device, while the older study employed a line source ignition). Ignition technique may have particular importance; the original line source ignition fires tended to spread extremely rapidly over the first portion of the bed and slowed to equilibrium,[2] while the point source ignition fires tended to accelerate to equilibrium ROS. Whether the fires stabalized at the same equilibrium ROS is open to speculation. As a result of the above factors, significant differences in the wind boundary layer could exist, causing differences in the head fire ROS values observed in the two studies and a proportionate inaccuracy in the BEHAVE predictions.

The second possible reason for the observed underpredictions is error in the estimation of moisture content of extinction (estimated at 34.0%). Rothermel's (1972) model does not provide for moisture of extinction calculation. The method used in BEHAVE is based on a simple regression line fitted to the extinction moisture values assigned to 8 of the 13 stylized fuel models. Further work has been done on this subject (Wilson 1985) but has not yet been incorporated into BEHAVE. Higher dead fuel moisture of extinction produces a "hotter" fuel model at all moisture levels and increases the moisture at which the fire is predicted to stop spreading (Burgan and Rothermel 1984). Careful examination of the data in Table 2 reveals that significant underprediction exists even in the no wind burns (burns 24, 25, 27), in which case the wind profile problem discussed previously is irrelevant. It appears that the fuel model should be "hotter", which can be achieved by increasing its moisture of extinction. The model can also be made "hotter" by changing the heat content of the fuel model to 22,183 kJ/kg, which is the mean heat content for ponderosa pine foliage reported by Kelsey et al. (1979). Both of the above modifications to the fuel model were tried simultaneously for the no wind case, but even then the underprediction only decreased to approximately half the initial value.

CANADIAN FBP SYSTEM:

As shown in Figures 1 and 2 and in Table 2, the Canadian FBP System consistently overpredicted the observed head fire ROS by 20 to 350%. Several possible explanations could be contemplated; however, there are two primary reasons: the experimental design and the wind speed estimation.

The experimental design contravenes the basis for the design of the Canadian FBP System. The FBP System was designed on the basis of small-scale experimental fires conducted under natural conditions. The laboratory fires conducted may or may not be representative of wildland fires conducted under the same environmental conditions. Factors possibly contributing include the absence of a forest stand, short-range spotting (<5m) that is accounted for automatically by the FBP System and is totally absent, fuels present in a natural setting that contribute to fire behavior in a minor way are lacking, and possible convection column effects on the fire behavior.

The conversion of the wind tunnel wind speed to an equivalent 10-m open wind speed is weak, to say the least. The range of factors documented in the literature as stated previously is large. Since the FBP System, like any other system for fire behavior prediction, is highly sensitive to changes in wind speed, small errors in this arena can cause massive prediction errors. The conversion factor chosen was somewhere in the middle of the potential range, thus a larger factor would amplify the prediction error and a smaller factor would reduce the prediction error. The argument presented for the wind profile in the U.S. BEHAVE system also likely has merit in the Canadian FBP System, i.e., it is unlikely that the wind profile simulated in the laboratory wind tunnel is precisely equivalent to that found in field conditions. Indeed the pattern of error observed in Figure 2 indicates increasing deviation from the observed ROS with increasing wind speed. Since the Canadian ROS prediction is based on empirical field research data, the pattern portrayed is likely more representative of wildland relationships (at least in this fuel type). This observation may indicate that wind tunnel wind speeds not only are not equal to field wind speeds (when they relate to forest fire ROS) but are also not linearly related.

As shown in Table 2, the ROS for the series of fires conducted with the lower fuel bulk density (13.1 kg/m^3) were fairly accurately predicted by the FBP System. This might lead us to believe that fuel bulk density is a factor in the prediction error problem; however, the original field study to document the C-6 fuel type had a fuel bulk density of 21.0 kg/m^3 (Van Wagner 1968), very close to the higher fuel loading value 26.0 kg/m^3, thus nullifying this argument.

Finally, the last possible explanation has to do with the original data upon which the C-6 fuel type is based. The data was collected from a single location, introducing a possible fixed bias in the application of the fuel type range.

Summary

The goal of this study was to compare the results of two methods of predicting head fire ROS with the observed head fire ROS. As with any model, it would have been possible to tinker with the input variable values until a good correlation was obtained, but that was not the point. The simple results from this limited laboratory study indicate that the BEHAVE fire behavior prediction system consistently underpredicted observed laboratory head fire ROS, while the Canadian FBP System overpredicted head fire ROS. Explanations can be postulated for the prediction errors observed in both systems; however, since BEHAVE was based on laboratory test fire results, a better fit to the data than was observed would be expected.

A number of reasons for the prediction errors were presented, but the most influential factor is the wind speed and the associated wind profile above the fuel. Observed head fire ROS is very sensitive to changes in wind speed, thus any predictive model must also be sensitive to changes in wind speed. How well any system for fire behavior prediction will work depends on the accuracy of the local (fire site) wind information. Small-scale perturbations in the ambient wind field will affect the head fire ROS for a short period of time; however, over the long run these minor variations should cancel out.

Endnotes

[1] Van Wagner, C.E. 1988. Personal Communication, October 20.

[2] Rothermel, R.C. 1989. Personal Communication, February 23.

References

ALBINI, F.A. AND R.G. BAUGHMAN. 1979. Estimating windspeeds for predicting wildland fire behavior. USDA For. Serv. Res. Pap. INT-221.

ALEXANDER, M.E. 1985. Estimating the length-to-breadth ratio of elliptical forest fire patterns. Pages 287-304 In Proc. Eighth Conf. Fire For. Meteorol. (Apr. 29-May 2, Detroit, Mich). Soc. Am. For., Bethesda, MD. SAF Publ. 85-04.

ALEXANDER, M.E., B.D. LAWSON, B.J. STOCKS, AND C.E. VAN WAGNER. 1984. User guide to the Canadian Forest Fire Behavior Prediction System: rate of spread relationships. Environ. Can., Can. For. Serv., Fire Danger Group. Interim edition. [First Printing - July 1984; Revision & Second Printing - September 1984].

ANDERSON, H.A. 1982. Aids to determining fuel models for estimating fire behavior. USDA For. Serv. Gen. Tech. Rep. INT-122.

ANDREWS, P.L. 1986. BEHAVE: Fire behavior prediction and fuel modeling system--BURN subsystem, part 1. USDA For. Serv. Gen. Tech. Rep. INT-194.

ANDREWS, P.L. AND D.J. LATHAM. 1984. BEHAVE: A knowledge-based expert system for predicting wildland fire behavior. In Proceedings, Summer computer simulation conference, July 23-25; Boston, MA; La Jolla, CA; Society for Computer Simulation; Vol. 2:1213-1218.

BAUGHMAN, R.G. AND F.A. ALBINI. 1980. Estimating midflame windspeeds. Pages 88-92. In Proc. Sixth Conf. Fire For. Meteorol. (Apr. 22-24, Seattle, Wash.). Soc. Am. For., Washington, D.C.

BERGEN, J.D. 1971. Vertical profiles of windspeed in a pine stand. For. Sci. 17:314-321.

BROWN, J.K. 1970. Ratios of surface area to volume for common fine fuels. For. Sci. 16:101-105.

BURGAN, R.E. AND R.C. ROTHERMEL. 1984. BEHAVE: Fire behavior prediction and fuel modeling system--FUEL subsystem. USDA For. Serv. Gen. Tech. Rep. INT-167.

CANADIAN FORESTRY SERVICE. 1984. Tables for the Canadian Forest Fire Weather Index System. Environ. Can., Can. For. Serv., Ottawa, Ont. For. Tech. Rep. 25. Fourth edition.

CATCHPOLE, T. AND N. DE MESTRE. 1986. Physical models for a spreading line fire. Aust. For. 49(2):102-111.

COOPER, R.W. 1965. Wind movement in pine stands. Georgia Forest Res. Pap. 33.

FONS, W.L. 1940. Influence of forest cover on wind velocity. J. For. 38:481-486.

KELSEY, R.G., F. SHAFIZADEH, AND D.P. LOWERY. 1979. Heat content of bark, twigs, and foliage of nine species of western conifers. USDA For. Serv. Res. Pap. INT-261.

LAWSON, B.D., B.J. STOCKS, M.E. ALEXANDER, AND C.E. VAN WAGNER. 1985. A system for predicting fire behavior in Canadian forests. Pages 6-16. In Proc. Eighth Conf. Fire and For. Meteorol. (Apr. 29-May 2, Detroit, Mich.). Soc. Am. For., Bethesda, MD. SAF Publ. 85-04.

MCALPINE, R.S. 1988. The acceleration of point source fire to equilibrium spread. M.Sc. Thesis, Univ. Mont., Missoula, Mont.

ROTHERMEL, R.C. 1967. Airflow characteristics--wind tunnels and combustion facilities Northern Forest Fire Laboratory. USDA For. Serv., Missoula Mont.

ROTHERMEL, R. C. 1972. A mathematical model for predicting fire spread in wildland fuels. USDA For. Serv., Res. Pap. INT-115.

ROTHERMEL, R. C. 1983. How to predict the spread rate and intensity of forest and range fires. USDA For. Serv. Gen. Tech. Rep. INT-143.

ROTHERMEL, R.C. AND H.A. ANDERSON. 1966. Fire spread characteristics determined in the laboratory. USDA For. Serv., Res. Pap. INT-30.

SCHUETTE, R.D. 1965. Preparing reproducible pine needle fuel beds. USDA For. Serv., Res. Note INT-36.

STOCKS, B.J., B.D. LAWSON, M.E. ALEXANDER, C.E. VAN WAGNER, R.S. MCALPINE, T.J LYNHAM, AND D.E. DUBE. 1988. The Canadian system of forest fire danger rating. In Proc. Conference on Bushfire Modelling and Fire Danger Rating systems (July 11-12, 1988, Canberra A.C.T.). CSIRO Div. For. and For. Prod., Natl. Bushfire Res. Unit, Canberra, A.C.T., Australia.

VAN WAGNER, C.E. 1968. Fire behaviour mechanisms in a red pine plantation: field and laboratory evidence. Can. Dep. For. Rural Develop, For. Branch, Ottawa, Ont. Publ. No. 1229.

VAN WAGNER, C.E. 1969. A simple fire-growth model. For. Chron. 45:103-104.

VAN WAGNER, C.E. 1971. Two solitudes in forest fire research. Can. Dept. Environ., Can. For. Serv., Inf. Rep. PS-X-29.

VAN WAGNER, C.E. 1977. A method of computing fine fuel moisture content throughout the diurnal cycle. Fish. and Environ. Can., Can. For. Serv., Inf. Rep. PS-X-69.

VAN WAGNER, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Govt. Can., Can. For. Serv., Ottawa, Ont. For. Tech. Rep. 35.

WILSON, R.A., Jr. 1985. Observations of extinction and marginal burning states in free burning porous fuel beds. Combust. Sci. Tech. 44:179-193

Modelling Diurnal Fuel Moisture Behavior

D.F. POTTS
University of Montana
Missoula, Montana

G.A. MORRIS
Intermountain Fire Sci. Lab.
Missoula, Montana

Abstract

The current BEHAVE fine fuel moisture model used to predict diurnal trends in fine fuel moisture, is based on the Canadian Fine Fuel Moisture Code modified to account for solar heating of fuels. Field validation revealed that the model consistently underestimated nighttime fuel moisture recovery and subsequent morning fine fuel moisture content. While it is possible that the adsorption and desorption rate constants are responsible for some of this apparent modelling deficiency, the real blame probably falls on the inadequacy of shelter-height temperature and humidity estimates of the actual conditions near the ground surface.

This paper describes proposed modifications to the BEHAVE fine fuel moisture model. Rapid nighttime radiational cooling to the surface dew point "target" is modelled using modified procedures originally developed by Brunt and Groen. Immediately following rain, surface dew point temperature is assumed to be the same as surface temperature. Surface dew point temperature is brought to equal shelter-height temperature if it has been 15 days or longer since the last rainfall. The Brunt and Groen procedures are again used at sunrise to rapidly raise surface temperatures from their nighttime minimum to the daytime maximum air-surface temperature difference predicted by Byram and Jemison's procedure.

Preliminary model validation against fuel moisture and corresponding meteorological data sets obtained in Montana and in Arizona showed excellent promise. Further validation with Australian field data is planned. Work is underway to improve model performance under full or partial canopy cover.

Résumé

L'actuel modèle de la teneur en humidité du combustible léger BEHAVE utilisé pour prédire les tendances diurnes de la teneur en humidité du combustible léger est basé sur l'Indice canadien de la teneur en humidité du combustible léger, modifié pour prendre en compte le réchauffement par le soleil des combustibles. Les activités de validation au champ ont révélé que le modèle sous-estimait régulièrement l'augmentation de l'humidité du combustible pendant la nuit et sa teneur en humidité du matin. Bien qu'il soit possible que les constantes du taux d'adsorption et de désorption soient responsables d'une partie de cette incapacité apparente du modèle, la faute est probablement véritablement attribuable au manque de précision des estimations de l'humidité et de la température au niveau de l'abri thermométrique des conditions régnant vraiment près de la surface du sol.

Le présent document décrit les modifications proposées au modèle de la teneur en humidité du combustible léger BEHAVE. Le refroidissement rapide du rayonnement à la tombée de la nuit pour atteindre le point de rosée "ciblé" à la surface du sol est modélisé à l'aide de méthodes modifiées, élaborées à l'origine par Brunt et Groen. Immédiatement après la pluie, la température du point de rosée en surface est présumé être le même que la température en surface. La température du point de rosée à la surface du sol est portée à être égale à la température du point de rosée à la hauteur de l'abri thermométrique s'il n'a pas plu depuis 15 jours ou plus. Les méthodes de Brunt et Groen sont à nouveau utilisées au lever du soleil pour porter rapidement les températures en surface de leur minimum nocturne à la différence de température air-surface maximale prédite par les méthodes de Byram et Jemison.

Les travaux préliminaires de validation du modèle au regard d'ensembles de données sur la teneur en humidité du combustible et sur les conditions météorologiques correspondantes obtenus au Montana et en Arizona se sont avérés très prometteurs. D'autres activités de validation avec des données prélevées sur le terrain en Australie sont prévues. Des travaux se poursuivent en vue d'améliorer la performance du modèle avec un couvert complet ou partiel.

Introduction

A critical element of the BEHAVE system is the fine fuel moisture model which is based on the Canadian Fine Fuel Moisture Code (FFMC)(Anon. 1984), mod-

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

ified to account for solar heating of fuels (Rothermel et al. 1986). Field validation of the model revealed that it consistently underestimated nighttime fuel moisture recovery (Figure 1). We propose modifications to the model to more accurately simulate fuel temperatures and humidity following sunset and sunrise.

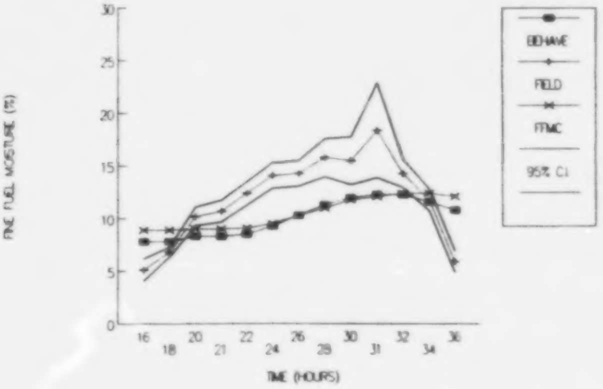


FIG 1. Measured fuel moisture vs. model prediction: south aspect, no canopy, August 25.

Methods

Nighttime radiational cooling of the surface to its dew point "target" is modelled using a modified procedure developed by Brunt (in Van Wijk 1963), which takes the form:

$$\Delta T = H_o\sqrt{4\alpha(t)}\,/\sqrt{K\pi}$$

where ΔT is the predicted temperature change during time interval, t; H_o is the steady state rate of energy loss from the surface; K and α are thermal conductivity and diffusivity, respectively.

Assuming an average surface emissivity of 0.98, longwave radiation loss from the surface to a clear sky, H_o, is about 80 W/m^2. Clouds and canopy reduce longwave loss proportionally. Convective gain, Hc, may also reduce H_o and is included with a simple boundary layer resistance formula:

$$Hc = pc\ (Ta - Ts)\ /\ ra \qquad (2)$$

where pc is air heat capacity; Ts is estimated surface temperature; Ta is screen-height temperature. For winds of 0 to 2 m/sec and 2 to 9 m/sec, boundary layer resistance, ra, is assumed to equal 250 and 125 s/m, respectively. Thus clouds, canopy and wind, or any of them in combination, may prevent surface temperatures from falling below screen-height temperatures.

Immediately following rain, surface dew point temperature is assumed to equal surface temperature, and except in unusual circumstances, higher than dew point temperature measured or estimated at shelter height. Shelter-height and surface dew point temperatures converge exponentially within 15 days of the last rain rainfall. Figure 2 shows typical dew point profiles at the start, middle and end of this process.

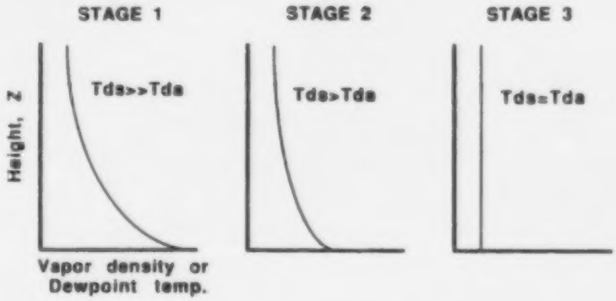


FIG 2. Dew point temperature profiles during 3 stages of surface evaporation.

The Brunt procedure is used again at sunrise to simulate rapid increase in fuel temperature from nighttime minimum. The rate of energy gain as the sun rises in the morning is much greater than the clear sky loss at night, so the fuel temperature increases very fast.

Results and Discussion

Figure 3 shows measured air and simulated fuel temperatures for the same site depicted in Figure 1. Note that fuel temperature converges with air temperature then rapidly falls past it at sunset. Nighttime minimum air and fuel temperatures occur at sunrise, then again rapidly invert to a strongly lapse temperature profile. The 5° C (40° F) noon air-surface temperature gradient is quite realistic and values such as this are seen often in the literature. Figure 4 shows the new fine fuel moisture estimates made with simulated temperatures.

References

ANON. 1984. Tables for the Canadian Forest Fire Weather Index System. 4th ed. Dep. Environ., Can. For. Serv., Ottawa, Ont. For Tech. Rep. No. 25. 48 pp.

ROTHERMEL, R.C. R.A. WILSON, G.A. MORRIS, and S.S. SACKETT. 1986. Modelling moisture content in fine dead woodland fuels: input to the BEHAVE fire prediction system. Res. Pap. INT-359. Ogden UT. USDA Forest Service, Intermountain Research Station. 61 pp.

VAN WIJK, W.R. (Editor) 1963. Physics of the Plant Environment. John Wiley and Sons, New York. 382 pp.

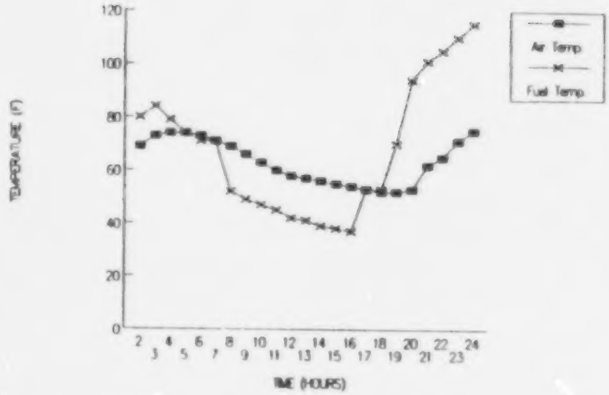


FIG 3. Measured air and simulated fuel temperatures: south aspect, no canopy, August 25.

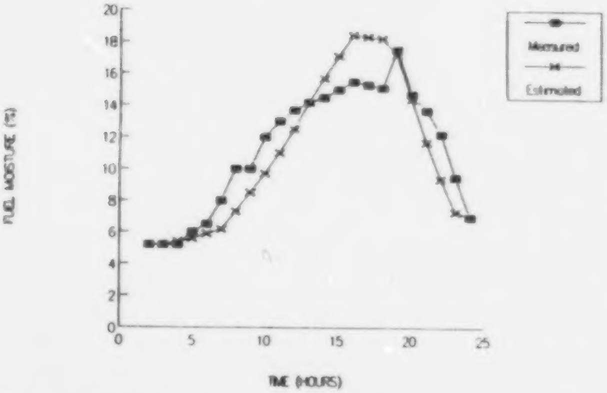


Fig 4. Measured and modified BEHAVE moisture estimates.

Water Dynamics of Peat Due to Subsurface Recharge

P.G. RIVARD, R.L. ROTHWELL AND P.M. WOODARD
University of Alberta
Edmonton, Alberta

Abstract

Wildfires are common in the Boreal Forests of the world. The fires in these forests are particularly troublesome because of the deep organic substrates commonly found there. Peat layers in these forests may be as deep as 3.0 m, hence holdover fires are a problem and mop-up costs can be inordinately high. The depth of peat is due in part to the cold and often poorly drained soils. The Canadian Forest Fire Weather Index System (FWI) is designed to predict fuel availability and when this information is coupled with measures of wind speed, fire behaviour forecasting is possible. Currently, the codes and indices of the FWI system are derived from measuring ambient air temperature, relative humidity, wind speed, and precipitation at a specified time of day throughout the fire season. The goal of our research is to assess the importance of subterranean water on fuel availability. Our basic objective was to discover if a relationship exists between actual peat moisture levels and the codes of the FWI, and if peat drainage significantly affects the ability of the FWI system to predict moisture changes in this peat material.

Résumé

Les feux de friches sont courants dans les forêts boréales du monde. Du fait des profonds substrats organiques qu'on y trouve généralement, ces feux sont particulièrement gênants. Dans ces forêts, les couches de tourbe peuvent avoir jusqu'à trois mètres de profondeur, d'où le problème de feux prolongés et des frais excessifs de nettoiement. La profondeur de la tourbe dépend, en partie, des sols froids et souvent mal drainés. L'indice Forêt-Météo Méthode Canadienne (IFM) vise à prévoir la disponibilité en combustibles. Si l'on combine cette donnée avec la mesure de la vitesse du vent, on peut prévoir le comportement du feu. À l'heure actuelle, les codes et les indices du système IFM dérivent de la mesure de la température de l'air ambiant, de l'humidité relative, de la vitesse du vent et des précipitations à un temps spécifié de la journée durant la saison des incendies. Notre recherche a pour objet d'évaluer l'influence de l'eau souterraine sur la disponibilité des combustibles. Notre objectif premier consistait à établir s'il existe un rapport entre les niveaux effectifs d'humité de la tourbe et les codes de l'IFM et si le drainage de la tourbe modifie beaucoup la capacité du système IFM de prévoir les changements d'humidité de la matière de la tourbe.

General

Peatlands are very common in those portions of the world where soils are cold and poorly drained. In Canada, about 118 million ha of peatlands have been identified. This represents a large amount of land area that is not very productive for growing trees. In Finland, the Soviet Union, Scandinavia and Great Britain, these lands are frequently drained to increase the available timber growing area (Hillman 1987). Draining can significantly lower the water table resulting in improved soil aeration and increased soil temperatures. These two benefits are known to promote tree root development and stem growth (Heikurainen 1964, Lieffers and Rothwell 1987 a,b). Tarnocai (1984) suggests most peatlands in Canada are suitable for some form of drainage.

Peatland drainage has significant implications for forest fire management. The removal of excess water from surface organic soils reduces substrate moisture contents which will increase the amount of available fuel, and thus fire hazard (Pyne 1984). Furthermore, how well the Fire Weather Index system (FWI) (Van Wagner 1974) estimates substrate moisture content (ie. fuel moisture content) in peatlands is unknown. The FWI estimates moisture contents and moisture codes based on the assumtion that the primary source of water comes from precipitation. In peatlands, organic substrates are wetted by precipitation and upward capillary movement of water from the subterranean water table, which is usually very close to the ground surface (0-30 cm) through the growing season.

The purpose of this research is to assess the applicability of the FWI system to drained and undrained peatlands, and in particular to determine the importance of subsurface water on fuel moisture contents and fire hazard ratings as they are currently calculated. Specific objectives are to test if FWI accurately describes moisture contents of drained and undrained peatlands, and provides reliable estimates of fire hazard (ie. fuel availability).

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

PEAT MOISTURE CONTENT

Peatlands are systems characterized by variable deposits of poorly drained organic soils, with a water table in close proximity to the surface, cool substrate temperatures and poor aeration. The cool conditions and low aeration inhibits decomposition and favours the growth and accumulation of dead plant material. Common live plant genera encountered in peatlands include: Spaghnum, Pleurzium, Pitilium and Hylocomium. The growth and mortality of these plants results in layering and increasing depth with the plants being compressed and decomposed into fine textured humic peat. The water retention capacity of peat is very high, characterized by volumetric water contents of 88-97% (Ivanov 1981). Peat deposits overlaying mineral soils and can be as deep as 3 m (Hillman 1987).

Peat moisture content is determined by soil structure and pore size distribution (Peerlkamp and Boekel 1960, Richard 1963, Puustjarvi 1963). Moisture content has been shown to be affected by peat type. Three peat group types have been described based on dominant constituents: Sphagnum peats (S peats), sedge peats (C peats), and woody peats (L peats) (Heikurainen and Huikari 1952, Heikurainen 1964). In general, peat water content is inversely proportional to matric suction and directly proportional to bulk density and total porosity (Paavilainen 1963). Fine textured peats (ie. highly decomposed) because of their smaller pore sizes have higher water contents and retention than coarse textured peats with large pore sizes. Peat water content is usually expressed volumetrically (cm^3/cm^{-3}) or gravimetrically (g/g) as ratios or percents. Therefore, the fuel availability in peats will be determined by peat types.

HYDROLOGY AND SOIL PHYSICS

The hydrology of a site can be described by the water balance, which illustrates a dynamic and complex balance of different components (Fig. 1). In a peatland the water balance can be divided into two subsystems, the groundwater system and the unsaturated zone (Fig. 2). Water content in the groundwater system is at saturation (100% by volume) and movement is by saturated flow in response to gravity. In the unsaturated zone water content is less than saturation (0.1-0.8 by volume) and movement is by capillary flow against gravity in response to matric suctions (ie. negative pressure).

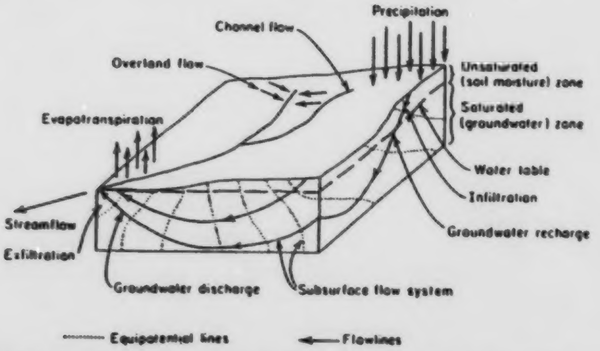


FIG 1. Schematic representation of the hydrologic cycle (extracted from Freeze and Cherry 1979).

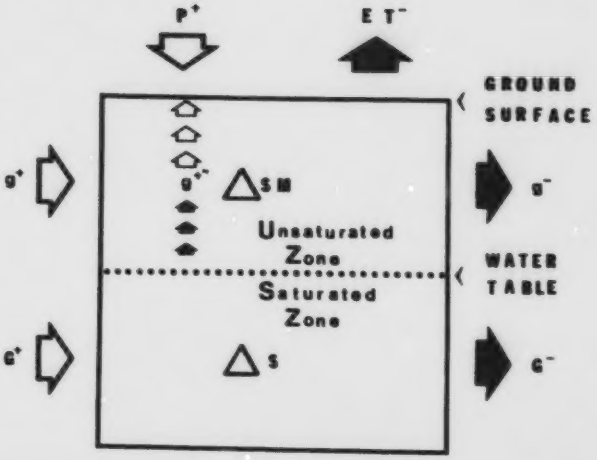


FIG 2. General definition of a water balance in a peat (Symbols are from equations (1) and (2) in text).

A water balance for the ground water system (Fig. 2) can be expressed as:

$$\Delta S = (P+G^{+}) - (ET + G^{-}) \qquad (1)$$

where ΔS = change in storage, P = precipitation, ET = evapotranspiration losses and G = groundwater flow in and out of the system. A water budget for the unsaturated zone is not as easy to describe. Inputs to the system, ignoring horizontal unsaturated flows, are from precipitation and upward capillary flow from the water table (Hanks and Ashcroft 1980). Precipitation inputs need to be adjusted to account from additions from the water table (ie. groundwater system). A water balance for the unsaturated can be expressed as:

$$\Delta SM = (P_{net} + g^{+'}) - ET \qquad (2)$$

where ΔSM = storage change in water content, P_{net} = net precipitation = P - WT, WT = water table rise from given rainfall expressed as a depth, $g^{+'}$ = upward capillary flow against gravity, from a high to low water content.

Peat moisture content or water storage in the unsaturated zone during rainless periods is controlled primarily by capillary flow from the water table. The shallow water table and fine textured humic peats allows the capillary fringe to extend to the soil/air interface, thereby insuring a steady upward flux of water due to steep gradients in moisture content. Several studies have attempted to determine a correlation between water table depth and peat moisture content. Heikurainen et al. (1964) in a summary and study described peat moisture content as a linear function of water table depth. The regression equations were significant, with correlation coefficients of $r = 0.94$-0.98.

The rate of capillary movement will be controlled largely by water potential gradients between the water table and ground surface. The more steep these gradients (ie. more negative) the greater potential for capillary flow. The rate of capillary movement however is reduced with increasing water table depth as the distance between the capillary fringe and ground surface is increased, and as tortuosity increases with depth. In the unsaturated zone upward flow is variable over time and dependent upon moisture content and pore size distributions of the peat (ie. matric potential).

In summary changes in storage or moisture content of unsaturated peat are determined by a balance between precipitation inputs at the surface, upward capillary flow from the water table in response to matric suctions, and evaporative losses. Upward capillary flow and its effect on moisture content will be determined by depth of the water table, climatic conditions and peat characteristics of moisture content and pore size distributions.

PEAT AND FIRE

Wildfires are common in the Boreal Forests of the world. Because organic matter accumulates, holdover fires are a problem and mop-up costs can be inordinately high.

The ease of ignition and sustained combustion of peat is related to its moisture content. Organic soils such as peat may also support combustion to a significant depth (Chandler et al. 1983). Buried combustible material can be ignited by a mild surface fire or by spontaneous ignition. Such ground fires are difficult to extinguish and can burn for several years, even under snow. Peat fires are considered to be duff fires, and include all fuels in the F (fermentation), and H (humus) layers (Pyne 1984).

Depending on fuel moisture, duff fires and surface fires may be linked in three ways (Martin et al. 1979). First, duff at moisture contents above 120% oven-dry weight (odw) does not burn, regardless of the character of the surface fire. Second, at moisture contents less than 30% by odw duff can burn independently of a surface fire, though most of this burning will take place after the passage of the flaming front. Third, between these fuel moistures, the amount of duff consumed will vary with the intensity of the surface fire.

FWI AND MOISTURE ESTIMATES

The Canadian Fire Weather Index (FWI) is a system that has been successful in estimating forest substrate moisture. The FWI is a measure of fire intensity and can be used as an estimate of fire severity (Lawson 1977):

$$I = H \cdot w \cdot r \qquad (3)$$

where;

I = Frontal fire intensity ($kW \cdot m^{-1}$)
~ FWI = Fire Weather Index
H = low heat of combustion of the fuel ($kJ \cdot kg^{-1}$)
~ constant
w = weight of fuel consumed per unit area ($kg \cdot m^{-2}$)
~ BUI = Build Up Index
r = Rate of spread of fire front ($m \cdot s^{-1}$)
~ ISI = Initial Spread Index

Thus in theory, the FWI is a measure of frontal fire intensity, and is calculated as:

$$FWI = \text{constant} \cdot BUI \cdot ISI \qquad (4)$$

Input variables to FWI include air temperature, relative humidity, wind speed and precipitation (Fig. 3) (Van Wagner 1974). The FWI provides numerical ratings that are regionally calibrated (Alexander et al. 1984). Three FWI codes are used to quantitatively estimate substrate moisture content (MC): fine fuel moisture code (FFMC), duff moisture code (DMC), and drought code (DC) (Alexander and Stocks 1987):

$$MC\%_{(FFMC)} = \frac{147.2(101-FFMC)}{59.5 + FFMC} \qquad (5)$$

$$MC\%_{(DMC)} = 20 + e^{(244.72-DMC)/43.3} \qquad (6)$$

$$MC\%_{(DC)} = 800\, e^{(-DC/400)} \qquad (7)$$

These equations are designed to predict the substrate moisture content at depths of 1-2, 5-10, and 10-25 cm

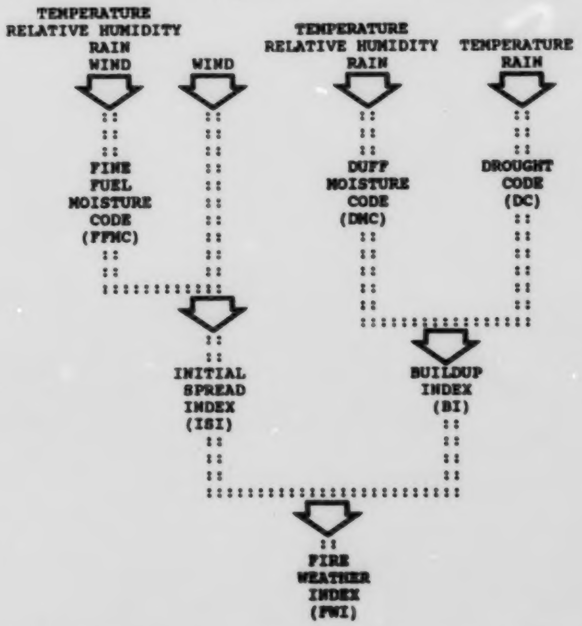


FIG 3. Input variables to the Canadian Forest Fire Weather Index System (FWI).

for the FFMC, DMC and DC, respectively. These estimates consider fuel moisture from surface input of moisture taking into account a drying rate on a day to day basis. However, this system as it is currently designed does not consider water input from subsurface water recharge.

At present, how well the FWI estimates substrate moisture content in peatlands is unknown. In the United States at least one additional fuel class will be added to their National Fire Danger Ranging System to represent organic soils, tundra and deep duff litter (Deeming 1988). Determination of peat moisture content during the fire season in Canada is important given the large area of peatlands and their potential for silvicultural drainage.

Summary and Preliminary Results

As previously discussed, theory indicates: (1) the hydrology of peatlands is affected by meteorological variables, (2) moisture content of peat in the unsaturated zone is related to water table depth, (3) capillary rise in peat is related to water table depth and hydraulic conductivity of the substrate which is a function of depth and substrate type, and (4) relationships exist to estimate the moisture content of forest soils with the FWI which may be applicable to peatlands.

Our preliminary results suggest that moisture contents of drained and undrained peats correlated well with the DC of the FWI (Fig. 4), which by definition is designed to describe the moisture content of compact, organic layers (Van Wagner 1974, Alexander and Stocks 1987). The strength of this relationship was attributed to the strong correlation between DC and water table depth (Fig. 5). Preliminary conclusions were that water table depth is an important factor affecting peat moisture content, providing the capillary fringe extends upward to the ground surface.

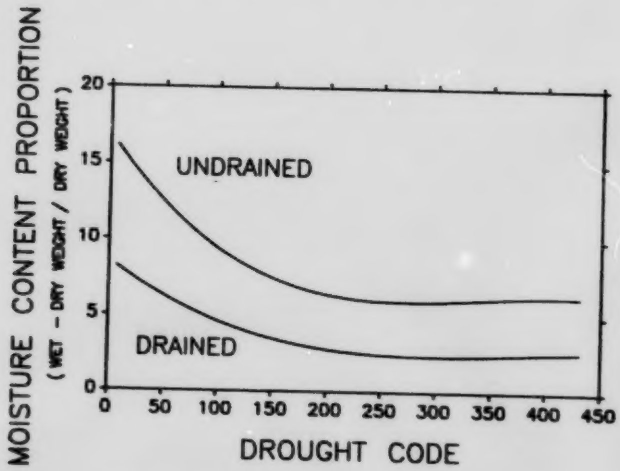


FIG 4. The relation between moisture content of peat and the Drought Code (DC) of the Fire Weather Index (FWI), for 1988 at the Saulteaux Peatland, Alberta, Canada.

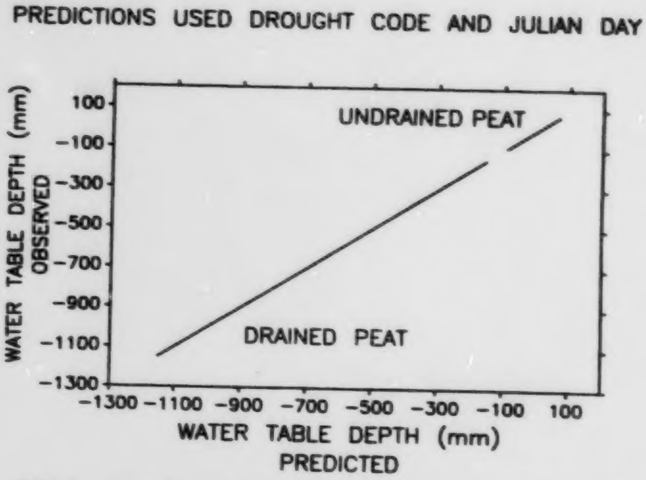


FIG 5. The relation between water table depth of peat and the Drought Code (DC) of the Fire Weather Index (FWI), for 1988 at the Saulteaux Peatland, Alberta, Canada

Future investigations will attempt to establish relationships between DC, water table depth, and peat moisture content by including temporal and spatial variation, hysteresis effects, and peat types. Further research is intended to provide information to be included in the "Accessory Fuel Moisture System" of the FWI (Alexander and Socks 1987) and better describe empirical relations within the Canadian Forest Fire Danger Rating System for forest management.

Literature Cited

ALEXANDER, M.E., B.D. LAWSON, B.J. STOCKS AND C.E. VAN WAGNER. 1984. User guide to the Canadian Forest Fire Behaviour Prediction System: rate of spread relationships. Interim Edition. Environ. Can., Can. For. Serv. Fire Danger Group.

ALEXANDER, M.E. AND B.J. STOCKS. 1987. Status of the Canadian Forest Fire Danger Rating System (CFFDRS) ... a progress report by the CFS Fire Danger Rating Group. Can. For. Serv., CFS, Edmonton, Alberta.

CHANDLER, C., P. CHENEY, P. THOMAS, L. TRABAUD, AND D. WILLIAMS. 1983. Fire in forestry: II forest fire behavior and effects. John Wiley and Sons, Inc., Toronto.

DEEMING, J.E. 1988. Fire-danger rating: the next 20 years. Fire Manage. Notes 49(4): 3-8.

FREEZE, R.A. AND J.A. CHERRY. 1979. Groundwater. Prentice-Hall Inc., Englewood Cliffs, N.J.

HANKS, R.J. AND G.L. ASHCROFT. 1980. Applied soil physics: soil water and temperature applications. Springer-Verlag, Berlin.

HEIKURAINEN, L. 1964. Improvement of forest growth on poorly drained peat soils. Int. Rev. For. Res. 1: 39-113.

HEIKURAINEN, L. AND O. HUIKARI. 1952. Turvelajin mikroskooppinen maarittaminen. Summary: The microscopic determination of peat types. Commun. Inst. For. Fenn. 40.5.

HEIKURAINEN, L., J. PAIVANEN AND J. SARASTO. 1964. Ground water table and water content in peat soil. Acta For. Fenn. 77: 1-18.

HILLMAN, G.R. 1987. Improving wetlands for forestry in Canada. Can. For. Serv., North. For. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-288.

IVANOV, K.E. 1981. Water movement in mirelands. (Vodoobmen v bolotnykh landshaftakh). Academic Press, London.

LAWSON, B.D. 1977. Fire Weather Index --- the basis for fire danger rating in British Columbia. Fish. and Environ. Can., For. Serv., Pac. For. Res. Cent., Victoria, B.C. Rep. BC-P-17.

LIEFFERS, V.J. AND R.L. ROTHWELL. 1987a. Effects of water table depth and substrate temperature on root and top growth of *Picea mariana* and *Larix laricina* seedlings. Can. J. For. Res. 16: 1201-1206.

LIEFFERS, V.J. AND R.L. ROTHWELL. 1987b. The effects of drainage on substrate temperature and phenology of some trees and shrubs in an Alberta peatland. Can. J. For. Res. 17: 97-104.

MARTIN, R., H.E. ANDERSON, W.D. BOYER, J.H. DIETERICH, S.N. HIRSCH, V.J. JOHNSON, AND W.H. MCNAB. 1979. Effects of fire on fuels: a statement of knowledge review. USFS Gen. Tech. Rep. WP-13.

PAAVILAINEN, E. 1963. Turpeen vesipitoisuudesta ja pohjavesipinnasta. Summary: On water content of peat and ground water level. Suo 4: 8-9.

PEERLKAMP, P.K. AND P. BOEKEL. 1960. Moisture retention by soils. Versl. Mede. Comm. Hydrol. Onderz.T.N.O. 5: 122-138.

PUUSTJARVI, V. 1963. Turpeen vesitaloudesta. Summary: On the water economy of garden peat. Suo 14: 56-62.

PYNE, S.J. 1984. Introduction to wildland fire: fire management in the United States. John Wiley and Sons, Inc. Toronto.

RICHARD, F. 1963. Wasserhaushault und entwasserung von weideboden. Ibid. 39: 245-269.

TARNOCAI, C. 1984. Peat resources of Canada. Natl. Res. Counc. Can., Ottawa, Ontario. Publ. 24140.

VAN WAGNER, C.E. 1974. Structure of the Canadian Forest Fire Weather Index. Environ. Can., For. Serv., Ottawa, Ontario. Publ. No. 1333.

Mieux s'informer pour mieux protéger

R. PROULX
Ministère de l'Energie et des Ressources
Charlesbourg, Québec

Résumé

Pour maintenir un service de qualité à un coût compétitif, les organismesde protection des forêts peuvent recourir au système centralisé de gestion des incendies forestiers. Sous un tel système, la planification et le contrôle de la détection et du combat des feux sont assumés, au niveau d'une vaste région, par un groupe restreint de personnes. Ce groupe doit pouvoir compter sur une information complète, de qualité, et disponible à temps. Les progrès réalisés dans trois techniques de pointe, à savoir l'ordinateur, la télédétection et les sciences de la gestion ont abouti à la mise au point de systèmes très perfectionnés de gestion informatisée des incendies.

Abstract

Forest fire protection agencies can make use of centralized management information systems to provide quality service at a competitive cost. With such a system, a small group of people can plan and monitor fire detection and firefighting activities in a very large geographical area. The group must be able to count on complete, high-quality information being available in good time.

The development of advanced fire protection systems has been made possible by progress in three areas--computers, remote sensing and management science.

Introduction

Au Québec, comme ailleurs au Canada, des pressions s'exercent en vue de minimiser les pertes dues aux feux de forêt. Elles viennent surtout:

- du public (il veut se sentir à l'abri des catastrophes lorsqu'il circule en forêt);
- de l'industrie et du gouvernement (ils investissent annuellement des centaines de millions de $ dans l'aménagement des forêts).

La plupart du temps, l'amélioration des résultats doit s'effectuer dan sun contexte de restrictions budgétaires. Il faut donc viser à mieux utiliser les ressources existantes.

Le système centralisé de prise de décision constitue l'une des clés de l'amélioration de la performance. Sous un tel système, quelques personnes ont la responsabilité de détecter et de combattre efficacement les incendies forestiers dans une grande région (pouvant couvrir jusqu'à 150 000 km^2).

Ce groupe doit pouvoir compter sur une information complète, de qualité et disponible au bon moment.

L'auteur propose d'examiner le cas du Québec:

- d'abord, en revoyant le contexte et l'organisation de protection des forêts;
- ensuite, en abordant plus spécifiquement le système d'information organisationnel qui est en cours d'implantation.

LE CONTEXTE ET L'ORGANISATION

Les statistiques et l'expérience nous enseignent que "l'homme" demeure inefficace dans le combat des grands incendies forestiers. Peu de feux d'envergure ont pu être maîtrisés par la seule intervention humaine, en dépit des sommes importantes et des efforts investis dans le combat. Ces incendies s'éteignent généralement d'eux mêmes, faute de combustible disponible ou suite à un changement marqué des conditions du temps.

Les gestionnaires de la ressource forestière doivent être prêts à accepter un certain niveau de pertes dues aux feux d'envergure, à coup sûrles plus significatifs quant aux dommages qu'ils causent.

L'amélioration de l'efficacité des systèmes de protection contre l'incendie passe plutôt par la réduction du nombre de grands feux.

Au Québec, les responsables de la protection des forêts reconnaissent la justesse de ce constat. L'objectif fondamental des Sociétés de conservation en fait foi: prévenir les incendies forestiers par une action soutenue de sensibilation et détecter rapidement les débuts de feux de façon à pouvoir intervenir le plus tôt possible alors qu'ils sont de dimension réduite. Depuis plusieurs années, la poursuite de cet objectif avec des moyens de plus en plus modernes et efficaces a permis d'améliorer les résultats. Le tableau 1 indique en effet que depuis 1972, la superficie moyenne des feux a diminué de moitié par rapport à la période équivalente précédente.

Présenté au 10iéme Congrés sur les incendies et la métérologie Forestière les 17 au 24 avril 1989 à Ottawa, Canada.

Tableau 1 - Incendies forestiers au Québec
moyenne selon les périodes

Périodes	Nombre de feux/année	Sup. affectée annuell.(ha)	Sup. des feux (ha/feu)
1956 à 71	885	61 835	70
1972 à 87	1 044	36 244	35

Le contrôle d'une situation de feux multiples pose, aux responsables de la protection des forêts, des problèmes de gestion de leurs ressources d'intervention. Il faut parfois faire face à plusieurs feux en une période de quelques heures. (Le 27 mai 1986 par exemple, la foudre a allumé en un seul après-midi 38 incendies concentrés dans les territoires de deux Sociétés de conservation).

En pareil cas, il est nécessaire d'intensifier la détection aux moments propices et d'accroître la capacité d'attaque initiale. Pour ce faire, l'organisation de protection doit: 1-être en mesure de prévoir les situations potentiellement difficiles et 2-posséder la flexibilité et la mobilité lui permettant de diriger effectifs et matériels vers les zones à risque élevé d'éclatement des feux et vers les incendies prioritaires. Le système centralisé de gestion des incendies et la coordination provinciale de la lutte facilitent grandement la concrétisation de ces deux caractéristiques.

Au coeur du système, on retrouve le quartier général de lutte (QGL), véritable centre nerveux du combat dans chaque Société de conservation.

Au plan provincial, un centre de coordination de la lutte (CCL) dont le personnel est chargé de surveiller le déroulement des activités et de déployer les ressources en fonction des besoins régionaux et des priorités.

Au Québec, la structure opérationnelle permettant de protéger 520 000 km² est schématisée à la figure 1.

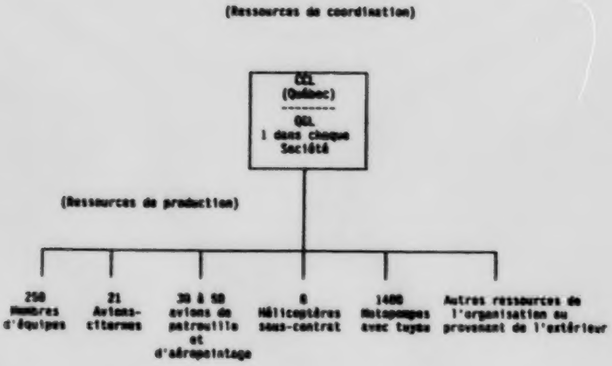

(Ressources de coordination)
CCL
(Québec)
QGL
1 dans chaque Société
(Ressources de production)
250 Membres d'équipes
21 Avions-citernes
30 à 50 avions de patrouille et d'aéropointage
6 Hélicoptères sous-contrat
1400 Motopompes avec tuyau
Autres ressources de l'organisation ou provenant de l'extérieur

FIG 1. Structure opérationnelle

Le succès du système centralisé dépend de la qualité de l'information mise à la disposition des personnes oeuvrant dans les QGL et au CCL. L'organisation doit pouvoir compter sur une composante destinée à la collecte des données et à la présentation des synthèses de l'information la plus récente sur les variations affectant l'environnement et les incendies forestiers. Cette composante s'appelle: le Système de gestion en protection des forêts (SGPF).

LE SYSTEME DE GESTION EN PROTECTION DES FORÊTS (SGPF)

Les progrès réalisés dans trois techniques de pointe, à savoir l'ordinateur, la télédétection et les sciences de la gestion, ont abouti à la mise au point de systèmes perfectionnés de gestion informatisée des incendies qui offrent la possibilité d'un renouveau total dans les opérations d'interventions.

Développés par l'Institut forestier national de Petawawa (IFNP) et expérimentés en grande partie à la Société de conservation de l'Outaouais, ces systèmes visent d'abord l'identification des problèmes mais il est aussi prévu qu'ils pourront un jour suggérer des scénarios de solutions. L'objectif ultime du SGPF est de prévoir à l'avance les incendies forestiers, leur impact et le résultat de l'application de diverses stratégies d'intervention.

L'INFRASTRUCTURE ET LE RÉSEAU

Tel que prévu au plan directeur provincial élaboré en 1984, le système repose sur un ensemble d'ordinateurs de type "mini" de marque DIGITAL (Vax 730, 750, 780 et micro Vax) qui sont reliés entre eux selon un réseau en étoile tel qu'illustré à la figure 2.

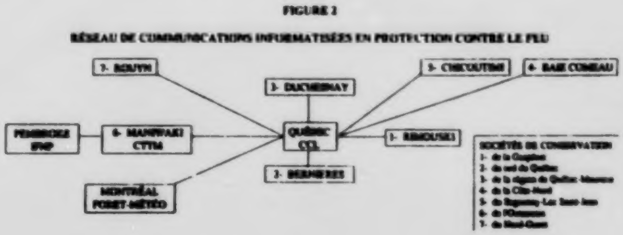


FIGURE 2
RÉSEAU DE COMMUNICATIONS INFORMATISÉES EN PROTECTION CONTRE LE FEU
7- ROUYN
3- DUCHESNAY
5- CHICOUTIMI
4- BAIE COMEAU
PEMBROKE IFNP
6- MANIWAKI CTTM
QUÉBEC CCL
1- RIMOUSKI
2- BERNIÈRES
MONTRÉAL FORET-MÉTÉO
SOCIÉTÉS DE CONSERVATION
1- de la Gaspésie
2- du sud de Québec
3- de la région de Québec-Mauricie
4- de la Côte-Nord
5- du Saguenay-Lac-Saint-Jean
6- de l'Outaouais
7- du Nord-Ouest

FIG 2.

Le logiciel QNET, développé spécialement pour ce réseau, permet de transférer, de façon efficace et à un coût réduit, les données entre le CCL et les QGL des Sociétés de conservation. La plupart des transferts d'information s'effectue de façon automatique selon un horaire pré-établi.

L'ordinateur central est en outre relié à celui de Forêt Météo du Service de l'environnement atmosphérique, à Montréal. Cette portion du réseau permet la redistribution des prévisions du temps et des autres produits de Forêt-Météo.

Pour faire produire cette quincaillerie, le Québec, avec l'aide du service Canadien des forêts, a mis sur pied le Centre de transfert technologique de Maniwaki (CTTM). Son principal mandat consiste à faciliter et accélérer le transfert des technologies informatisées aux Sociétés de conservation et au centre de coordination de la lutte du MER. En plus de développer les logiciels d'application, le CTTM voit à produire la documentation et à former les personnes mises en contact avec le SGPF.

LA STRUCTURE GÉNÉRALE DU SGPF

Il convient de noter que plusieurs éléments du système sont encore au stade du développement et de l'expérimentation comme l'indique la figure 3.

Outre le logiciel de communication, le SGPF comprend actuellement:

a) les bases de données historiques (feux et informations météorologiques des dix dernières années);
b) les programmes de calcul de l'indice Forêt Météo de la méthode canadienne;
c) les modèles de prévision des feux de causes humaines et de foudre;
d) les logiciels permettant d'effectuer les synthèses régionales et provinciales des informations et leur présentation graphique;
e) le service de courrier électronique.

Certains programmes, comme les modèles de prévision des feux, ont été élaborés à partir des conditions propres à la région de l'Outaouais. Certes, quelques années seront nécessaires pour les évaluer en fonction du contexte de chaque région et les ajuster si nécessaire.

Le transfert des autres éléments sera entrepris lorsque ceux ci seront considérés opérationnels. A ce moment ci, il est prévu:

a) de développer, suite aux résultats obtenus de l'expérimentation en cours présentement, un réseau de radars de pluie similaire à celui des détecteurs de foudre déjà existant;
b) d'expérimenter un capteur infrarouge pour la détection des débuts de feux à partir de l'avion de patrouille;
c) d'intégrer, au programme de propagation de feux, les principaux types de couverts forestiers obtenus de l'inventaire forestier numérisé et des données satellitaires classifiées.
d) de compléter la numérisation des courbes de niveau du terrain;
e) d'expérimenter les modèles de planification des patrouilles aériennes et d'optimisation du déploiement des ressources selon les stratégies d'attaque initiale des feux;

LE COÛT

Des investissements de près de 2 millions de dollars ont été consentis depuis la mise au point du plan directeur. Le tableau 2 montre en outrequ'annuellement, l'opération du système s'élève à plus d'un million de dollars dont 82 % sont consacrés à la main d'oeuvre spécialisée en informatique et en électronique.

A titre indicatif, le budget de 1988 89 pour la protection des forêts s'élève à 28 millions $ (en excluant le coût d'extinction des feux).

Conclusion

Le SGPF permet la collecte et la synthèse rapides des données concernant:

- le danger de feu;
- les feux de foudre potentiels;
- les feux en activité;
- les prévisions météorologiques.

Déjà, les résultats obtenus suscitent l'adhésion des utilisateurs du système.

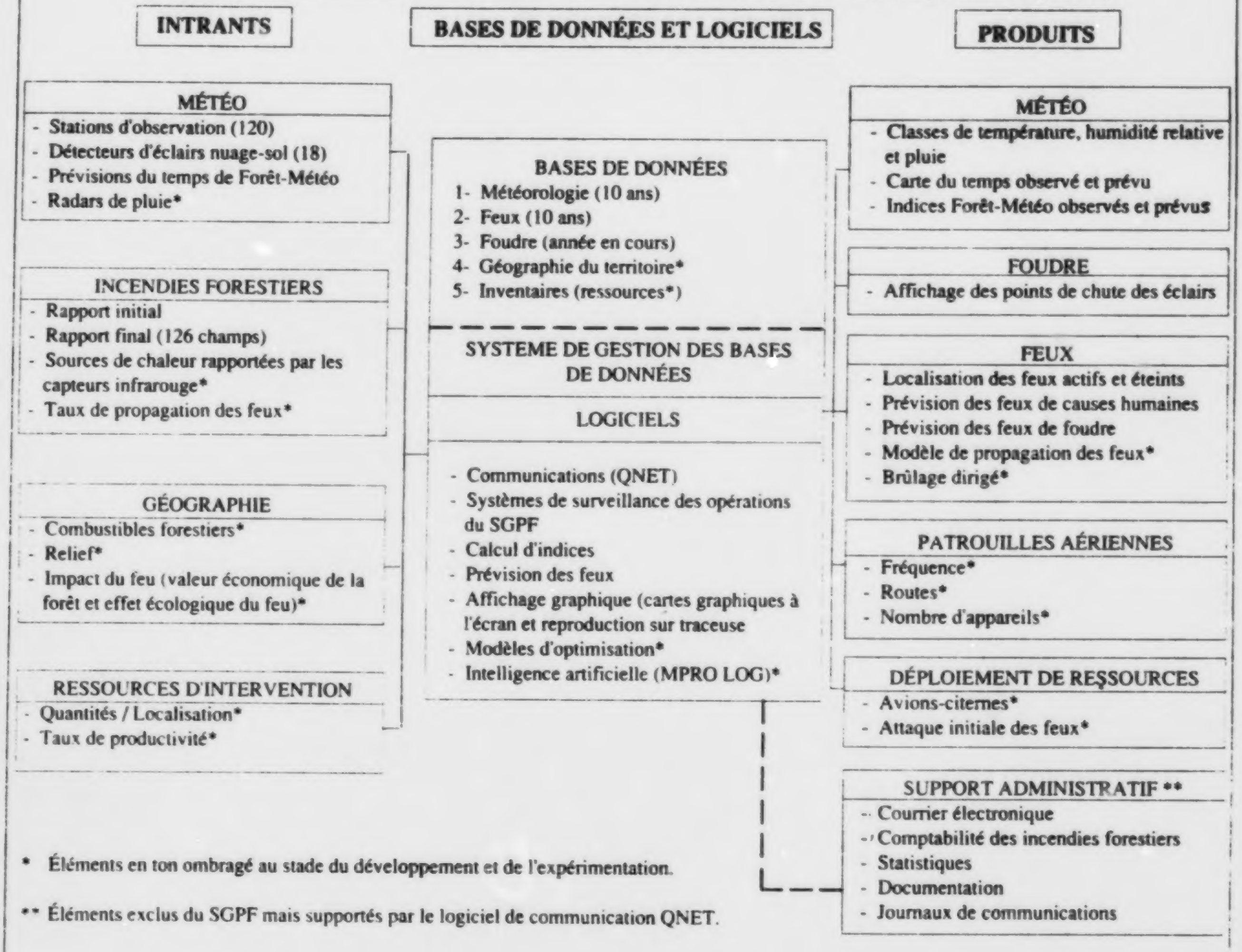
Tableau 2 - Coût du SGPF

Elément	Dépenses (en milliers de $)
Immobilisations	
- Achat de matériel informatique	1 160,0
- Achat et installation des détecteurs de foudre	700,0
- TOTAL	1 860,0
Coût annuel d'opération	
- Communications	
Informatiques	25,0/an
• Détecteurs de foudre	60,0/an
- Développement et entretien des logiciels d'application	
• CTTM	500,0/an
• Sociétés de conservation et SPCF	400,0/an
- Entretien des systèmes informatiques	115,0/an
TOTAL	1 100,0/an

Trois facteurs importants maximisent les chances de réussite dans l'application de cette technologie:

FIGURE 3

STRUCTURE GÉNÉRALE DU SYSTÈME DE GESTION EN PROTECTION DES FORÊTS (SGPF)*



INTRANTS

MÉTÉO
- Stations d'observation (120)
- Détecteurs d'éclairs nuage-sol (18)
- Prévisions du temps de Forêt-Météo
- Radars de pluie*

INCENDIES FORESTIERS
- Rapport initial
- Rapport final (126 champs)
- Sources de chaleur rapportées par les capteurs infrarouge*
- Taux de propagation des feux*

GÉOGRAPHIE
- Combustibles forestiers*
- Relief*
- Impact du feu (valeur économique de la forêt et effet écologique du feu)*

RESSOURCES D'INTERVENTION
- Quantités / Localisation*
- Taux de productivité*

BASES DE DONNÉES ET LOGICIELS

BASES DE DONNÉES
1- Météorologie (10 ans)
2- Feux (10 ans)
3- Foudre (année en cours)
4- Géographie du territoire*
5- Inventaires (ressources*)

SYSTEME DE GESTION DES BASES DE DONNÉES

LOGICIELS
- Communications (QNET)
- Systèmes de surveillance des opérations du SGPF
- Calcul d'indices
- Prévision des feux
- Affichage graphique (cartes graphiques à l'écran et reproduction sur traceuse
- Modèles d'optimisation*
- Intelligence artificielle (MPRO LOG)*

PRODUITS

MÉTÉO
- Classes de température, humidité relative et pluie
- Carte du temps observé et prévu
- Indices Forêt-Météo observés et prévus

FOUDRE
- Affichage des points de chute des éclairs

FEUX
- Localisation des feux actifs et éteints
- Prévision des feux de causes humaines
- Prévision des feux de foudre
- Modèle de propagation des feux*
- Brûlage dirigé*

PATROUILLES AÉRIENNES
- Fréquence*
- Routes*
- Nombre d'appareils*

DÉPLOIEMENT DE RESSOURCES
- Avions-citernes*
- Attaque initiale des feux*

SUPPORT ADMINISTRATIF **
- Courrier électronique
- Comptabilité des incendies forestiers
- Statistiques
- Documentation
- Journaux de communications

* Éléments en ton ombragé au stade du développement et de l'expérimentation.

** Éléments exclus du SGPF mais supportés par le logiciel de communication QNET.

- le recrutement des experts requis pour assurer le bon fonctionnement du système;
- la formation des utilisateurs;
- l'amélioration du système par des évaluations périodes.

A moyen terme, il est prévu que le SGPF permettra à l'organisation de se positionner afin de continuer de fournir un service efficace en utilisant mieux les habiletés disponibles.

Références

Le présent texte a été préparé à partir de la publication suivante:

PROULX, R., 1988. Un système d'information organisationnel (SIO) pour la protection des forêts contre le feu. Revue L'Aubelle no. 64, Ordre des ingénieurs forestiers du Québec, Formation Continue, cours no. 5, 6 p.

Application of a PC-Based Fire Management Information System In New Brunswick

W.G. CLOWATER
Forest Fire Protection Branch
New Brunswick Dept. of Natural Resources and Energy
High John Fleming Forestry Centre
Fredericton, New Brunswick

U. FEUNEKES
I.R. METHVEN
R/EMS Research Ltd.
Fredericton, New Brunswick

Abstract

The fire season of 1986 resulted in enormous losses that led to evaluation of the needs of the Forest Fire Protection Branch of the New Brunswick Department of Natural Resources and Energy. Identified in this evaluation was the lack of a fire management information system. This resulted in a cooperative venture with R/EMS Research Ltd. to develop a PC-based system tailored to the needs and budget of the province. The system now includes the ability to calculate and interact with the codes and indexes of the Canadian Forest Fire Weather Index (FWI) System and to display these geographically at each region; to analyze the historical weather and FWI System database through a series of graphing procedures, to display historical fires on a map of the province by one or more attributes, and predict fire growth for individual fuel types. Problems with availability of hardware, staff training, computer expertise, and dedication of staff to fire management information systems have been encountered, but these have been and are being overcome. The objectives of developing a basic, cost-effective, fire management information system has been accomplished.

Résumé

Des pertes énormes ont été encourues lors de la saison des incendies de 1986. Ces pertes ont menées à l'évaluation des besoins de la direction de la protection contre les incendies de forêt du ministère de l'énergie et des ressources naturelles du Nouveau-Brunswick. Cette évaluation a indentifier le manque d'un système d'information de gestion des incendies. Il en résulta une entreprise risquée en coopération avec R/EMS Research Ltd. qui avait pour objectif de développer un système sur PC taillé aux besoins et au budget de la province. Le système permet la calculation et l'interaction avec les codes et les indices de l'indice de la méthode canadienne Forêt-Météo (IFM) et permet l'affichage de ceux-ci géographiquement à chaque région. Il permet aussi l'analyse de la météo historique et la base de données du système IFM à travers d'une série de procédures à base de graphiques, d'afficher les feux historiques sur une carte de la province par un ou plusieurs attributs, et prédire l'accroissement de l'incendie par les types de combustibles. Des problèmes ont été encourus au niveau de la disponibilité de matériel, des besoins en formation, d'expertise informatique et de la dévotion du personnel à un système de gestion d'information, mais ceux-ci ont été surmontés, ou on est en mesure de les sur monter. Un système de base à bon marché de gestion d'information sur les incendus à été élaboré, et ainsi on a rencontré notre objectif.

Introduction

New Brunswick is the first province in Canada to adopt a totally PC-based fire management information system. The impetus behind this development was a coincidence of factors including serious fire losses in 1986, a limited budget with respect to purchase of new systems, the power of contemporary personal computers, and the development of local expertise in fire management software systems. This coincidence resulted in a productive association that led to the development and implementation of a PC-based system, which is described in this paper.

Background and Development

The 1986 fire season in New Brunswick resulted in the worst losses in 40 years. During a one week period in May, 60 fires were burning which consumed over 39,000 hectares or 0.63% of the productive forest land. One fire near Tracadie (in Northeastern N.B.)

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

burned 28,000 hectares of prime, 40-year-old jack pine and spruce. When one considers that all Crown lands in New Brunswick are allocated for timber production, that the forest industry is responsible for 45% of all exports, and that there is a looming wood supply problem, then this was an event of major concern. In addition, there were significant social losses since several homes and many camps and cottages were destroyed in the fires.

An analysis of the events identified a number of problems, but one of the most significant had to do with the issue of preparedness. In other words, neither the regions nor the Provincial Fire Centre were prepared for the magnitude of the fire activity that erupted during that week. In the absence of preparedness and rapid initial attack, once the fires escaped, control became very difficult if not impossible due to low humidities (15% - 19%) and the lack of night-time recovery. The basic question faced by the Department, therefore, was how did the fire situation develop to the level it did without being noticed? To answer this we need to look at the fire intelligence or information system that was in place at the time.

The 1986 Situation

The base of the fire information system in 1986 was a fire weather network composed of 40 weather stations scattered across the province. While the distribution and location of this network was far from perfect, the density was probably as high as anywhere in Canada with one station for every 1,800 km^2 on average. Unfortunately, although the weather network was in place, a system for handling the weather data efficiently, and translating it into useful and timely fire management information was not.

Noon weather data were forwarded to the Provincial Fire Centre by telephone each day, telexed to the Atmospheric Environment Service in Halifax by 1400, the Canadian Forest Fire Weather Index codes and indexes calculated, and telexed back to the Provincial Fire Centre in Fredericton which forwarded them to the regions. This somewhat involved process often resulted in the regions not receiving the daily hazard information until after 1600 hours.

The problems associated with such a system are transparent. The hard copy output of over four hundred numbers did not constitute information - just another form of data. Given such a mass of data, the tendency is to look at the Fire Weather Index (FWI) only and ignore the other codes and indexes. On the 14th of May, for example, when the greatest proportion of fires broke out, 80% of the weather stations reported that the Fine Fuel Moisture Code (FFMC) was extreme while none of the FWI values were extreme. Other problems included the lack of opportunity to check and correct errors; the lack of opportunity to play 'what if' games with the weather data; the receipt of the results was too late to be of use in the current burning period; delays in the forecasted output; and the effective inaccessibility of the weather database for analysis, since it resided in a remote mainframe computer in another province.

The Situation in 1987

In the fall of 1986 Mr. Wayne Clowater, the newly appointed Director of Forest Protection, was fortunate enough to pay a visit to the Societé de Conservation de L'Outaouais in Maniwaki where he was exposed to the advanced state of contemporary fire management. Unfortunately, it was a case of the kid with the nose pressed against the window of the candy store with no money in his pockets - there was simply no budget available for the purchase and installation of such a large system. Fortunately, R/EMS Research Ltd., a consulting and personal computer software company specializing in fire management, was being incorporated in New Brunswick at the same time. By early 1987 some basic PC software had been developed, namely a program that would calculate the codes and indexes of the FWI System, create an accessible database, provide the user with a simple interactive capability, calculate the values for forecast weather, and display the current and forecast codes and indexes by classes on a map of the province. This was purchased by the New Brunswick Department of Natural Resources and Energy and was installed in time for the 1987 fire season. The software was designed to run on any IBM compatible PC, and in this case had to run on a basic Corona with a D300 printer. While the speed and resolution of the hardware were low, it did the job.

The Provincial Fire Centre now had control of its own weather data, hazard was displayed graphically to provide immediate information on where the problems were or might be on any given day (current or forecasted), hazard maps and tables were available for the whole province by 1400 hours, 24 hour forecasts by 1500 hours, and 12 hour forecasts by 0900 hours, and there was now some central clout to an organization that had been totally decentralized. There was, however, one major problem still to be solved: communication of the output to the regions. The only means of communication was by telecopier, and it could take up to six hours to transfer the information to all the regions.

In the fall of 1987 the Provincial Government froze the purchase of all computer hardware, which put a stop to plans for improving the speed and graphics capability of The Provincial Fire Centre system, and for solving the communications problem with the regions by providing them with an independent capability. R/EMS Research Ltd. was interested in developing a Beta test site for R/EMS software so an agreement was reached with the Provincial Fire Centre to fulfill this function. R/EMS then upgraded the Centre's hardware with an APCO 286 with EGA graphics, Goldstar colour monitor, and a Panasonic KX-P109li printer for the 1988 fire season.

The 1988 Fire Situation

Prior to the 1988 fire season the Board of Management granted an exemption on the hardware freeze and each of the regional offices was equipped with Coronas (CGA graphics) and printers, and the Provincial Fire Centre was able to purchase hardware to run the new generation of software. In the meantime R/EMS had continued to upgrade and develop new software and the following programs were installed: A Fire Weather Analysis Package to take full advantage of the weather and FWI System database that was now at the manager's fingertips; Interactive Tables to allow the user to play 'what if' games with the current and forecast weather to avoid surprises; a Fire Occurrence Display System to activate the historical fire database and display past fires geographically by any one or a combination of attributes, and a basic Fire Spread Model for forecasting fire spread, area, and perimeter by single fuel types.

The regions were equipped with software used at the Fire Centre the previous fire season, namely the Fire Weather Index Calculation and Display System. Weather was telephoned into the Provincial Fire Centre for processing and a subset of weather data from thirty stable stations electronically mailed back to the regions using ENVOY so that they could do their own processing and production of hazard maps. All regions now had the actual and 24 hour forecast hazard data by 1400 hours at the latest, and the 12 hour forecast incorporating overnight rain by 1000 hours. One region was able to FAX the hazard maps to each of its eight district offices almost immediately so that fire intelligence was now disseminated at all levels of the organization in a timely and effective manner. In addition the Provincial Fire Centre FAXED the hazard maps to a major land-holding forest industry, thereby taking the first step in involving the forest industries in fire intelligence and preparedness.

In two years, therefore, the province had moved from a zero capability in the processing of fire weather data and the generation of fire management information, to a rapid, effective, province-wide system that ensured that a 1986 fire season would not be repeated.

The 1989 Plans

The plans for 1989 include upgrading of the software at the regional level so programs and file structures are compatible, evaluating and improving the electronic mailing system to reduce costs, purchase of FAX machines for all the regional offices, installation of a computerized version of the Canadian Forest Fire Behaviour Prediction (FBP) System, replacement of the Fire Occurrence Display System with a new version, and final testing of a Fire Occurrence Prediction System.

Problems

The above developments were not without problems, since insertion of a computer-based system into an organization or group not familiar or comfortable with computers can encounter some resistance and difficulty. This is sometimes compounded when the software comes from outside the government, as in this case. Training and upgrading courses have been required, and these have helped greatly in the acceptance of the system. Response is now generally positive. Problems that still need to be addressed are: cost and flexibility of the communications systems, upgrading of regional software, lack of computer expertise within the Fire Centre or Regional Offices to deal with basic computer problems, high turnover of staff, the difficulty of staffing fire information positions with trained and experienced people seven days a week through the fire season, and pacing the development of fire management information systems to the capability of staff to exploit the systems fully.

Conclusions

The Forest Fire Protection Branch of New Brunswick has made enormous strides in the processing of fire weather and fire data and in the generation of timely, useable and effective information since 1986. Development is still in its initial stages, but the groundwork has been done to ensure that the valuable forest resources of the province are no longer placed at such high risk of destruction by fire.

Integrating Geographic Information Systems Into Fire Management

L. A. SALAZAR AND C. V. NILSSON
Pacific Southwest Forest and Range Experiment Station
Forest Service, U.S. Department of Agriculture
Riverside, California

Abstract

Wildland fire managers and planners rely heavily on information that describes environmental and sociological factors. Complex and dynamic interactions among these factors are commonplace, but difficult to model and portray in a useable and understandable way. And when dealing with large, multiple-fire situations, these interactions become even more difficult to track manually, let alone explain. Geographic information systems (GIS) enable the user to store vast amounts of data and to manipulate and analyze these data to provide information that is vital to fire planning and real-time decisionmaking. Because wildfires are such a spatially oriented phenomena, there are many potential uses of GIS technology in fire management. The USDA Forest Service's National GIS Plan will not meet all of fire management's needs because much of the necessary fire data is not universally used, defined, or shared. A special task group needs to be formed to develop a National Fire GIS Plan that addresses the specific needs and requirements of fire management. To simplify this effort and to coordinate with the National GIS Plan, it may be desirable to implement the same tasks identified in the national effort in the Fire GIS Plan. These tasks are organizational readiness, information base and structure, external coordination and oversight, technology procurement and integration, and implementation.

Résumé

Les gestionnaires de feu de friches et les planificateurs s'appuient fortement sur des données qui décrivent des facteurs environnementaux et sociologiques. Des interactions complexes et dynamiques entre ces facteurs sont courantes mais difficiles à modeler et à dépeindre d'une façon pratique et compréhensible. En situation de feux larges et multiples, il est encore plus difficile de dépister manuellement ces interactions, sans parler d'essayer de les expliquer. Les systèmes d'information géographique (SIG) permet tent à l'utilisateur de stocker d'énormes quantités de données, de les manipuler et de les analyser pour en tirer des renseignements d'une importance vitale pour la planification et la prise de décisions en temps réel.

Les feux de friches étant des phénomènes orientés dans l'espace, il existe beaucoup d'usages potentiels de la technologie du SIG qui s'applique à la gestion d'incendies. Le plan national SIG du USDA Forest service ne pourra rencontrer tous les besoins de la gestion des incendies parce que beaucoup de données reliées aux incendies ne sont pas utilisées, définies ou partagées de façon universelle. Il est nécessaire de former un groupe de travail special qui développer a un plan du SIG national d'incendie qui saura adresser les besoinset exigences spécifiques de la gestion des incendies. Afin de simplifier cet effort et de coordonner avec le plan du SIG national, il serait désirable de meltre en oeuvre les mêmes tâches identifiées dans l'effort national du plan du SIG d'incendies. Ces tâches sont la promptitude organisationnelle, la base et structure de l'information, coordination externe imprenus acquisition et intégration de la technologie, et la mise en oeuvre.

Introduction

Wildland fire management requires the integration of large amounts of information about environmental and societal factors, which are spatially and temporally dynamic. Complex interactions among these factors are commonplace, but they are also difficult to model and portray in an understandable way.

A geographic information system (GIS) is a specialized information processing technology designed to input, store, manipulate, analyze, and display spatially referenced data. Its primary purpose is to support organizational decisionmaking. GIS goes beyond traditional computer technology, which uses tabular data, by incorporating spatial relationships between objects or features. A GIS provides a set of x, y, and z coordinates that relate these tabular data to ground locations, and it performs mathematical operations on these data and their coordinates.

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

GIS is a complex and costly technology to implement. Substantial amounts of time and energy must be devoted to the planning and implementation of a GIS for it to succeed. Although there were many GIS failures initially, GIS users in the mid-1980's have demonstrated that this technology is no longer experimental and that it can work operationally.

The number of operational wildfire-related GIS systems is growing slowly. The Petawawa National Forestry Institute at Chalk River, Ontario, Canada, has been very active in this endeavor for many years. Since 1970, the focus of Petawawa's fire management decision support project has been on researching and developing the concepts and information processing methods necessary for a centralized fire management system (Kourtz 1984). The Okanogan National Forest in northern Washington has used an operational GIS for various wildfire management applications (Gum 1985), and more recently for resource applications.

Innumerable applications are possible when combining a fully operational GIS (with a complete and current data base) with such wildland fire management functions as fuel management, prevention, detection, presuppression, dispatch, suppression, and wilderness fire management. Beyond a spatial data base managing system, a GIS would also provide the medium for integrating the various fire-related systems (e.g., ALDS, AFFIRMS, FIRDAT, NIIMS, NFMAS) that are now used by the USDA Forest Service. This practice would reduce redundancy and create the potential for more efficient use of those systems.

A national plan has been developed and approved for implementing GIS technology within the USDA Forest Service. Its objective is to help achieve the agency's mission through better resource information analysis and graphical display (U.S. Dep. Agric. For. Serv. 1988). The design of the national plan emphasizes better communication and sharing of information among various staffs and across current administrative boundaries. To help achieve this objective, the types and amount of data that are shared throughout the National Forest System were explored in the initial stages of developing the National GIS Plan, with three levels of sharing defined: (1) corporate data that will be accessible and commonly understood and used agency-wide to support resource management decisions, (2) project data used to support specific projects or categories of work, and (3) staff data used to support staff work.

The Forest Service and its national GIS task forces will invest the greatest amount of time and energy in the corporate data set by developing a commonly understood language of terms, codes, and reference definitions. A large portion of fire management's data needs will be outside this data set because much of this information is not universal and is used only by fire staffs. This information may include: locations of fire starts, final fire perimeters, current and proposed fuelbreaks or firelines, locations of Fire Management Analysis Zones, travel times along roads and trails, weather station locations and their recorded data, fuel loadings or fuel models, locations of lightning strikes, hourly weather readings, or the location, type, and landscaping condition of buildings. Within the National GIS Plan, these fire-related data and their use have been recognized as a project-specific application of the GIS (Rains 1987).

This paper discusses the relationship of fire management to geographic information systems and to the National GIS Plan. It highlights the tasks and issues that will need to be considered in order to successfully integrate GIS into fire management within the USDA Forest Service.

Need For a Task Group

The complexity of implementing GIS to support fire-related GIS issues calls for the formation of a task group to systematically address the relevant issues. This task group will need to include fire management specialists, GIS specialists, researchers, as well as representatives from other cooperating agencies and organizations.

To simplify this "Fire GIS" effort and to coordinate with the National GIS Plan, it may be desirable to implement the same tasks identified in the National Plan within the context of fire management:

- Organizational readiness
- Information base and structure
- External coordination and oversight
- Technology procurement and integration
- Implementation

We will address each of these components and the issues that must be addressed in order to integrate GIS into fire management.

Organizational Readiness

The national GIS effort, as part of its organizational readiness component, is actively involved in cultivating awareness and understanding of the principles and objectives associated with implementing a Service-wide GIS. The fire organization will need to be aware not only of the national GIS, but of GIS and its capabilities as related to fire, because of the project aspect of many of fire management's needs.

Essential to promoting organizational readiness will be the development of implementation planning guidelines. The task group would need to address the following organizational issues:

1. Who will be involved in the use of a Fire GIS (fire management staffs, GIS specialists, researchers, cooperators)?
2. Where will the Fire GIS personnel be located?
3. What will be their organizational roles and responsibilities, and how will this impact their current position?
4. How will GIS responsibilities be distributed among the Boise Interagency Fire Center (BIFC),

Regions, Forests, Districts, Research Stations, and State and Private Forestry?

5. What key action items will need to be performed?

6. When should key action items be accomplished so that they coordinate with the National Plan?

7. How will the Fire GIS and all its associated personnel, training, data acquisition and conversion, hardware, and software be funded?

The Fire GIS task force will need to improve awareness throughout the fire staffs, emphasizing the benefits as well as the changes that will be involved in using a GIS for fire purposes. Fire management personnel, as ultimate users of the system, will need to be involved in the design phase to identify their information needs. GIS specialists with a preliminary background in fire will be needed to translate these user needs into application programs and system requirements. Also, to take full advantage of a GIS and its analytical capabilities, GIS specialists and users (to a somewhat lesser extent) must understand the technical issues behind a GIS, including the concepts of map projections, coordinate systems and georeferencing, data dictionaries, relational data base design and management, spatial interpolation, topological relationships, error modeling, and data uncertainties. Fire researchers will need to be trained in the theoretical aspects of GIS to be able to develop models and to use spatially related analytical techniques.

Information Base and Structure

A great deal of fire-related data will not be included as part of the corporate data set as defined by the National GIS Plan. Defining the information base and structure for fire management will need to include these steps: defining the overall objectives of integrating GIS into fire management; performing a survey of fire management information needs; defining the structure of the information base and identifying core fire data; and evaluating and testing the proposed objectives, information structure, and data base environments. We will briefly discuss each of these tasks in further detail.

By defining overall objectives, principles, and assumptions about the Fire GIS Plan we will gain an understanding of the role that GIS can and cannot play in fire management and planning. This task will need to consist of several "think tank" meetings to develop the blueprint of fire-related information needs. The documentation produced by this task will serve as focus and foundation to further develop, test, and refine the informational, technological, and organizational aspects of integrating GIS into fire management.

A survey of fire management information needs on National Forests would identify the kinds of data that are currently being used by fire management staffs. This survey will help to identify basic (i.e., raw) data versus interpreted (i.e., derived) data, categorizing these data in terms of their jurisdictional use, and standardizing the codes and terminology used to describe the data. Survey results will also indicate data needs that will not be a part of the corporate data set that may be of interest but were overlooked by a number of users.

Defining and documenting the information structure and data base environment for fire management needs will facilitate understanding and sharing of information about fire-related data within the task group, with other functions (e.g., timber management) within the USDA Forest Service, as well as externally with other federal agencies, states, counties, countries and universities. The activities needed to accomplish this task will include defining the needed functionality and characteristics of the data base environment, such as base map drafting requirements, map resolutions, data structure (e.g., raster or vector, or both), data accuracies, data currency requirements, map projections, update frequencies, inter-agency update coordination, data access restrictions (i.e., classified data) and allowable error (i.e., tolerances).

After the information needs and structure have been collected and defined, evaluation and testing will be needed to evaluate alternative ways of structuring the spatial and tabular data associated with the GIS and to interface it with the corporate data base. National Forests with varying degrees of fire activity should be involved in this evaluation and testing, making sure that most needs are being addressed.

External Coordination and Oversight

Because wildfires do not respect administrative boundaries, external coordination is extremely important when dealing with a fire-related GIS on a national level. As with the National GIS Plan, interagency GIS coordination should focus on those federal agencies or organizations with natural resource management missions, including the U.S. Geological Survey, Bureau of Land Management, National Park Service, Fish and Wildlife Service, and Soil Conservation Service. The National GIS Plan will address uniformity of definitions, accuracy, and formats for within-Forest Service exchanges. The Federal Interagency Coordinating Committee on Digital Cartography is developing and adopting common standards of content, format, and accuracy for digital cartographic data bases to be used by all Federal agencies. Not only will data bases have to be shared, but GIS procedures and principles will have to be coordinated, so that fire specialists can effectively interact with each other.

Beyond this interagency coordination, the Fire GIS Task Group will have to coordinate with the national GIS planning group, National Forests, states, counties, neighboring countries, and local public agencies with fire-related responsibilities, fire research organizations, universities, and other research institutions.

Of particular interest in this coordination effort will be the National Science Foundation's National Center for Geographic Information and Analysis (NCGIA), which was established in 1988 and is based at the University of California at Santa Barbara. The Center's goals are to: advance the theories, methods, and techniques in GIS; increase the number of experts in GIS and geographic analysis in participating disciplines; promote the diffusion of analysis based on GIS throughout the scientific community; and provide a central clearinghouse for information regarding research, teaching, and applications in GIS.

Oversight activities (as related to planned expenditures) will be involved with requirements from the Department of Agriculture, the General Services Administration, the Office of Management and Budget, and any congressional appropriation subcommittees that may be involved.

Technology Procurement and Integration

In the context of fire management, the objectives of the technology procurement component would be to identify fire management functional needs that will not be satisfied by the National GIS, to define the GIS hardware and software requirements that will satisfy these needs, and to develop or purchase the necessary hardware and software to fulfill these requirements.

HARDWARE

The functional requirements of some fire applications may make it necessary to supplement the standard GIS hardware acquired in the National Plan with additional work stations, specialized communication links, more powerful CPU's, increased disk storage space, or other specialized hardware (e.g., portable work stations, backup power supplies). Ascertaining the need for additional or enhanced hardware will have to be based on a comprehensive evaluation of fire management information and functional needs, including the amount of fire-related data that needs to be stored, the amount of processing and modeling that needs to be performed, and the quantity, timing, locational need (e.g., fire camps or staging areas), complexity, and required response times for information requests by fire staffs.

SOFTWARE

A number of different kinds of software will need to be considered in order to integrate GIS into fire management. These include the basic GIS software package, GIS applications software which is part of the national procurement, fire-related GIS application programs, extended GIS software functions, and other fire-related application programs and systems.

In the diverse environment of the USDA Forest Service, the GIS software selected in the national procurement plan will support the development of application programs. With this approach, vendors do not attempt to provide software that can meet the specific needs of every different type of user. Instead, most users will interact with the GIS through a standard set of application programs written specifically for the Forest Service environment and which enable them to manipulate, query, and display data in the standard data base. This standard set of programs will undoubtedly meet some, but not all, fire-management needs. In order to integrate GIS into fire management, those needs which will not be met by the national GIS will have to be identified, their processing and functional requirements defined, and their capabilities implemented in fire management-specific application programs.

In addition to the basic GIS software package, national application programs, and fire management-specific programs, spatial functions required to meet fire management needs, which are either unavailable in the GIS or represent an extension of the basic package, will need to be identified. For example, the relationship between fire behavior and topography and the potential for routing applications in fire suppression suggests that extended GIS functions for performing three dimensional modeling and network analysis will need to be included. Ties to non-GIS based application programs such as BEHAVE (Andrews and Latham 1984) or spotting models (Albini 1983) will also need to be considered. Fire spread models may also require the use of unconventinal data representations, such as hexagonal rather than square grid cells.

INTEGRATION WITH EMERGING TECHNOLOGIES

An important aspect of implementing GIS to support fire management needs will be integrating this technology with other emerging computer and related technologies. And to be cost-effective and successful, fire managers need to be aware of the problems, challenges, and opportunities presented by their future use.

Compact optical disks (CD) which can hold enormous amounts of data, are becoming more accessible and less expensive (Clark 1988). As an example of their data storage capabilities, it is possible to reduce the storage requirements of one of the largest geographic data bases in the world -- the Defense Mapping Agency's global terrain elevations -- from 900 computer tapes to 45 CDs (Morrison 1988). CD storage will better support fire management information needs because it will provide on-line access to large fire-related data sets, including hourly weather readings, crew and supply information, remote sensing imagery, and lightning strike locations. These data, when used in conjunction with data already in the GIS, will enable us to make better temporal comparisons and to provide more extensive inputs for research efforts.

Remote sensing technological improvements in spectral and ground resolutions, analytical capabilities, and interfaces with GIS's, provide many opportunities for the use of satellite imagery as input for vegetation typing and weather reporting. Currently, the best available satellite ground resolutions are in the 10- to 30-m range, but a Soviet satellite is recording data at 6-m resolution (Morrison 1988) and 5-m resolutions are presently being developed and incorporated into designs of future satellites. Improvements in spectral resolution will also provide better information on vegetation composition and condition.

The storage of U.S. Census Bureau data in a GIS-compatible format will be helpful for relating population densities, descriptions, and locations to human-caused fire occurrence potentials. The upcoming 1990 Census will use an automated mapping system called TIGER (Topologically Integrated Geographic Encoding and Referencing). TIGER files will include a computerized street map of the entire country, the official inventory of 1990 Census tabulation units, and a geocoding directory for relating addresses to the Census and coordinate locations.

Developments in Global Positioning Satellites (GPS) are also making them cheaper and more accurate and accessible. Readings of locations every second are possible, with accuracies within a few millimeters (Ware 1986). After wildfires the perimeters or interior islands could be walked or flown in a helicopter and recorded using a GPS. Also in the future, crew locations could be monitored during large fire situations. Study plot locations will also be easier to relocate for detecting temporal changes (e.g., revegetation) from the same spot.

Videodisc technology can be used to link oblique and panoramic imagery to 2 or 3-dimensional GIS perspectives. Also, aerial photography, parcel maps, historical photographs, close-up photographs, planning maps, and any other images that may be impractical to digitize and input as a GIS layer, can be cost-effectively stored on videodisc. They can then be electronically accessed through the GIS's relational data base (Hamilton et al. 1989). Interactive video can be used in wildland fire behavior training (Jenkins and Matsumoto-Grah 1987) or to familiarize crews with new areas or those that are obscured by smoke.

Expert systems (i.e., computer models of expert human reasoning) show promise for dealing with the large amount of data and interactions that are involved with fire management in a GIS context. Expert systems have been used for crew and equipment dispatching in southwest Quebec, Canada (Kourtz 1987), managing wilderness fires (Saveland et al. 1988), determining fire behavior and damage in Kakadu National Park, Australia (Davis et al. 1986), fire prevention planning (Schmoldt and Bradshaw 1988), referencing fire effects knowledge (Fischer 1987), and designing fire prescriptions (Reinhardt et al. [in press]). Particularly useful for GIS applications will be future expert systems that: can "see" and interpret maps, are capable of inductive reasoning, and can perform logical analysis.

Implementation

The National GIS implementation phase calls for the training of managers and users, data acquisition and entry, and the installation of GIS hardware and software. The same tasks will need to be performed for the Fire GIS, but their focus will be on fire-related GIS training, data, hardware, and software. Users, such as dispatchers, fire managers, and incident commanders will need training in the use of fire-related application programs, but they will probably need little GIS knowledge beyond that provided by the National Plan.

The National GIS Plan projects data acquisition, conversion, and entry at the national, regional, and local levels. Fire or other designated staffs will be responsible for collecting, entering, maintaining, updating, and analyzing fire-related, non-corporate data. This could be a major undertaking, considering that an estimated 75 percent of the cost of procuring and implementing GIS is associated with data acquisition, conversion, and entry (U.S. Dep. Agric. For. Serv. 1988). Priorities and timelines will need to be established and acted on as soon as the various task groups form their final recommendations for necessary data requirements and guidelines.

Fire GIS applications programs will need to be installed and tested on-site using existing data sets. Fire GIS hardware will also need to be installed and interfaced with existing hardware as part of this phase.

Summary and Conclusions

To integrate geographic information systems into fire management, a task group needs to be formed to identify, evaluate, and perform the necessary tasks for such an integration. This task group should consist of fire management specialists, GIS specialists, researchers, as well as managers from cooperating agencies and organizations.

To simplify this effort and to coordinate with the National GIS Plan, it may be desirable to implement the same tasks identified in the National Plan within the context of fire management. This process will be complex, requiring the development of policies and procedures, large costly data bases, application programs, training packages, and integration procedures for emerging technologies. Active steps must be taken to integrate GIS technology into fire management, and the sooner that these steps are taken, the smoother will be the transition to an operational Fire GIS. A coordinated Fire GIS will reduce redundancy in developing standards and procedures and it will establish consistency throughout the Forest Service's fire community. A focused process will also provide many opportunities for fire researchers to become involved with GIS technology for data integration and analysis.

GIS technology shows great potential for assisting fire managers, planners, and researchers, and we have only scratched the surface of this potential in this paper. Recent catastrophic wildfires throughout the world have resulted in increased scrutiny and interest in fire organizations and their decisionmaking processes. The public and the courts will likely demand to know the reasoning behind certain decisions, and they will challenge some of those decisions. The GIS can be used to provide information for decisionmaking, but it cannot and should not be used to make the decisions. Decisionmaking should always remain a human activity. Also, because of the dynamics of environmental and sociological factors and the complexities of the data input process, we can never expect to have a perfect and completely up-to-date data base. Wildland fire managers need to combine their expertise with GIS-derived information to devise the best strategies possible.

References

ALBINI, F.A. 1983. Potential spotting distance from wind-driven surface fires. USDA For. Serv. Res. Paper INT-309, Intermountain. For. and Range Exp. Sta.

ANDREWS, P.L., D.J. LATHAM. 1984. BEHAVE: A knowledge-based expert system for predicting wildland fire behavior. P. 1213-1218 In W.D. Wade, ed., Proc. 1984 summer computer simulation conference, Boston, MA, July 23-25, 1984, Soc. for Computer Simulation, La Jolla, CA.

CLARK, S.R. 1988. Optical disk technology: potential in geographic information systems. P. 541-549 In Proc. GIS/LIS 88, San Antonio, TX., Nov. 30 - Dec. 2, 1988, Amer. Cong. on Surveying and Mapping, Amer. Soc. for Photogrammetry and Remote Sensing, Assoc. of Amer. Geographers, Urban and Regional Information Systems Assoc., Falls Church, VA.

DAVIS, J.R., J.R. HOARE, AND P.M. NANNINGA. 1986. Developing a fire management expert system for Kakadu National Park, Australia. Jour. of Env. Manage. 22:215-227.

FISCHER, W.C. 1987. The fire effects information system. USDA For. Serv. Gen. Tech. Rep. PSW-101, Pacific Southwest For. and Range Exp. Stn.

GUM, P.W. 1985. Computerization of fire dispatch utilizing satellite imagery "Okanogan Project". p. 315-325 In Proc. Pecora 10 Remote sensing in forest and range resource management, Fort Collins, CO, Aug. 20-22, 1985, Amer. Soc. for Photo. and Remote Sensing, Falls Church, VA.

HAMILTON, M.P., L.A. SALAZAR, AND K.E. PALMER. Geographic Information Systems: Providing information for wildland fire planning. Fire Technology. 25(1):5-23.

JENKINS, M.J., K.Y. MATSUMOTO-GRAH. 1987. Videodisc/microcomputer technology in wildland fire behavior training. USDA For. Serv. Gen. Tech. Rep. PSW-101, Pacific Southwest For. and Range Exp. Stn.

KOURTZ, P. 1984. Decision-making for centralized forest fire management. The Forestry Chronicle. 60(6):320-327.

KOURTZ, P. 1987. Expert system dispatch of forest fire control resources. AI Appl. in Natural Res. Manage. 1(1):1-8.

MORRISON, D.C. 1988. The science of where. Government Executive. April:34-38.

RAINS, M.T. 1987. The role of GIS in spatial resource information management a Forest Service perspective. P. 111-121 In Proc. GIS '87 Second Annual Intl. Conf., Exhibits, and Workshops on Geographic Information Systems, San Francisco, CA, Oct. 26-30, 1987, American Society for Photogrammetry and Remote Sensing, American Congress on Surveying and Mapping, Falls Church, VA.

REINHARDT, E.D., A.H. WRIGHT, AND D.H. JACKSON [In press]. An advisory expert system for designing fire prescriptions. Ecological Modeling.

SAVELAND, J.M., M. STOCK, AND D.A. CLEAVES. 1988. Decision-making bias in wilderness fire management: implications for expert system development. AI Applications 2(1): 17-29.

SCHMOLDT, D.L., W.G. BRADSHAW. 1988. A cumulative Delphi approach to knowledge acquisition. P. 149-162 In Proc. Third Annual Rocky Mtn. Artificial Intelligence Conf., Denver, CO, June 13-15, 1988, US West Advanced Technologies and Rocky Mountain Society for Artificial Intelligence, Denver, CO.

U.S. DEPARTMENT OF AGRICULTURE, Forest Service. 1988. National GIS plan - geographic information system. Washington, D.C.

WARE, R. 1986. GPS The high accuracy environment. Professional Surveyor. May/June: 12-49.

Application of Fire Growth Simulation Models in Fire Management

P. L. ANDREWS
Intermountain Research Station, Forest Service
U.S. Department of Agriculture
Missoula, Montana

Abstract

A variety of fire management activities can include the use of a fire growth simulation model for decision support. The design of the simulation must depend on the application. Potential applications are discussed including short-term projections on a going fire, assigning priorities to multiple fires, long-term projection for a going fire, long-term projection for a simulated fire, long-term successional modeling, escaped fire situation analysis, long-term economic planning, and modeling potential fires within the urban wildland interface.

Résumé

Diverses activités de gestion des feux de forêt qui pourraient inclure la modélisation du taux d'accroissement des incendies peuvent servir à supporter les décisions. La conception d'un système de simulation depend de l'application. Les applications potentielles sont examinées incluant les projections à court terme d'un feu en marche, l'assignation des priorités lors de fuex multiples, des projections à long terme d'un feu en marche, des projections à long terme d'un feu simulé, la modélisation de la succession à long terme, l'évaluation des possibilités de suppression, la planification économique à long terme et la modélisation d'incendies potentiels dans la zone ou la forêt et la ville se rejoignent.

Introduction

Fire management decisions are often based in part on the use of mathematical models that offer a consistent and repeatable method of providing quantitative fire behavior parameters. The core of most fire management systems in the United States is a deterministic mathematical model for steady-state fire burning through uniform surface fuel (Rothermel 1972). When a fire growth simulation model is available, I am certain that it will be used as a decision support tool in many fire management decisions. In this paper I discuss potential applications.

Fire Growth Simulation Model

A fire growth simulation model could be used to calculate the spread and intensity of a fire burning through variable fuel and terrain, under weather conditions that vary over both space and time. The need for a fire growth simulation model is not a new idea (Van Gelder 1976, Kourtz et al. 1977, Frandsen and Andrews 1979). There is currently a lot of interest in this area of work, so much that I will not attempt to review it in this paper. A major reason for the recent activity is that computer hardware and software is now able to support this application. In particular, Geographic Information Systems (GIS) offer a means of storing, manipulating, and displaying spatial data.

Fire growth simulation models will likely hold a prominent place in the next generation fire behavior/fire danger rating systems in the United States. It will take a major effort to develop and fully integrate fire growth simulation models into the fire management decision process. This paper attempts to contribute to that effort by identifying decisions that will be aided by fire growth modelling. One of the three major tasks involved in developing systems of the future is the determination of user needs (Rothermel and Andrews 1987). We hope this paper will stimulate people to think in specific terms about how a fire growth simulation model can support fire management decisionmaking in the future.

A fire growth simulation model only approximates actual fire growth regardless of how much effort is put into developing it. Law and Kelton's (1982) state-

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

ments about simulation models in general certainly apply to the simulation of fire growth: "A simulation model should always be developed for a particular purpose. Indeed, a model valid for one purpose may not be valid for another. ... A simulation model should be validated relative to a specified set of criteria, namely, the criteria that will actually be used for decision making."

Short-Term Projection On a Going Fire

Projections of fire spread and intensity around the perimeter of a fire are used in selecting potential control points and in assigning suppression forces to a wildfire. Short-term prediction of the behavior of a wildfire is both an art and a science. Fire experience is essential to the prediction process. Fire Behavior Analysts (FBA's) currently use their experience and the steady-state fire model in making predictions according to methods described by Rothermel (1983). Vectors of fire spread are plotted from several key points around the perimeter. The overall fire growth is then sketched on a topographic map based on the FBA's judgment. Personal judgment is also used in defining the input for the calculations. For example, windspeed and direction are determined from measurements, forecasts, and topography.

A fire growth simulation model must be streamlined and easy to use to be useful as a tool to a FBA. Producing projections in a timely manner is critical. The simulation should produce maps that show current fireline location and probable fire growth given the best weather forecast. It may be used to develop a range of likely fire positions based on varied forecast information.

The model should be easy to use but not so fixed that personal expertise and judgment are not authorized. Although the simulation must include a method of determining variable windspeed and direction over complex terrain, there should also be an option to enter wind vectors directly. The FBA and meteorologist on a fire team may want to assign windspeeds rather than use the results of a wind model. Another example of the need for flexibility is related to the fuel information stored in the data base. Fuel mapping from interpreted satellite imagery is not 100% accurate. Although this procedure is adequate for many applications, it may not be acceptable for real-time fire behavior prediction if the small percentage that is misclassified falls in front of the fire. We must also allow for the possibility of correctly classified fuel having changed since the data base was last updated.

Assigning Priorities to Multiple Fires

In multiple large fire situations a fire growth simulation model could be used to compare the spread potential among fires competing for suppression resources. This could provide a basis for setting priorities relative to the kind of forces that should be assigned to each fire. In conjunction with economic models, this would help decision-makers judge the alternatives that are available to them.

Long-Term Projection For a Going Fire

There is a real need for a well-defined method of making long-term projections of the growth of a specific fire. This relatively new need results from fire management policies that in many cases allow options other than full suppression. A fire can be declared either a prescribed fire or a wildfire. And there are several levels of appropriate suppression action that can be taken on a wildfire. An important decision is made when a new fire start is declared a prescribed fire or a wildfire. A primary element to be considered is potential fire behavior. It is expensive and difficult to later reverse a decision that designated a fire as a prescribed fire.

An interagency fire management fire policy review team was established to review policies of the U.S. Departments of Agriculture and the Interior on fire management because of the fires in the Greater Yellowstone Area during the summer of 1988 (USDA/USDI 1988). Among other things, the team recommended that "Current fire management plans must be strengthened by ... Including a comprehensive set of criteria which will be used in deciding whether or not to allow natural ignitions to burn as prescribed fires." And "Line officers certify daily that adequate resources are available to ensure that prescribed fires will remain within prescription, given reasonably foreseeable weather conditions and fire behavior."

Regardless of how good a fire growth simulation model is, it is not possible to make fire behavior predictions without reliable weather forecasts. Nevertheless, fire managers must base a decision on what a fire might do weeks or months into the future, well beyond a 3-day forecast. Gaming can be used with a simulation model to examine possible outcomes based on historical weather records. Such questions as: What if the weather is the same as last year?, What if it is the most extreme weather on record?, What if a dry cold front moves through each of the next 5 weeks?, can be asked and answered instantaneously. Given this information fire managers will have to determine whether their decisions should be based on most probable or on worst case conditions and assess the element of risk that they are willing to accept.

Although this approach has been applied to some extent to currently available methods (Rothermel et al. 1988, Lukens and Krebs 1987), it is tedious and time consuming to look at more than a few possibilities. A fire growth simulation model could produce a multitude of projections based on various potential weather patterns in a relatively short time frame. The results could be presented as probabilities. In most cases it is not important to know exactly where the fire will be on a given date, but rather whether it will reach a certain critical boundary before it goes out, or whether it will get larger than a given critical size.

In addition to being used as support for the decisionmaker, the results of fire growth simulations can be used as a means of communication. The resulting maps can be a focus for discussion among agency people. They can be used as a means for communicating the bases for decisions and recommendations to line officers and also for communicating the status of the fire and its potential to the public and the press.

Long-Term Projections of Simulated Fires

Simulations such as those described above for ongoing fires can also be done for hypothetical fire starts and used in the planning process. Simulation of fires in various locations in the management area under a range of weather conditions would help define an acceptable level of risk for designating a fire as a prescribed fire.

Development of the Absaroka-Beartooth Wilderness fire management plan used available technology to estimate the potential size and intensity of historical fires under the assumption that suppression action had not been taken (Keown 1985). Historical fires were matched with weather records, and potential fire behavior was calculated. The results suggested that fires would be relatively small, with low potential for large stand replacement fires. A simulation would allow this approach to be expanded to project fire behavior under weather conditions other than those under which historical fires occurred and to simulate additional hypothetical fire starts.

Long-Term Successional Modeling

Simulation models have been developed to assess the long-term ecological impacts of a fire management policy (van Wagtendonk 1985, Keane et al. in press). Such a simulation is run for a long period (e.g., 200 years) under various fire regimes (e.g., full suppression, lightning fire, 10-year fire interval). The simulation includes models for stand development and fuel accumulation. The use of GIS and a fire growth model will allow the addition of spatial relationships.

Escaped Fire Situation Analysis

The Forest Service objective for wildfire suppression on National Forest System lands is to suppress wildfires at the minimum cost consistent with land and resource management objectives. An escaped fire situation analysis (EFSA) is conducted when a wildfire escapes initial suppression action. It is used to determine the most appropriate suppression strategy for the particular situation. Reasonable suppression alternatives are identified, analyzed, and evaluated. Evaluation criteria include estimated suppression costs, resource loss, and environmental, social, and political considerations. The probability of success of a given suppression strategy is dependent upon factors such as fuel, weather, topography, fire behavior, and the availability and effectiveness of suppression forces. Probability of success is most often based upon judgment of members of the fire overhead team (Chambers 1985).

A fire growth simulation model would bring consistency into the development of the EFSA. The estimation of how big a fire is going to get or where it is going to burn under various suppression alternatives would be more objective. In addition, evaluation of long-term ecological effects could be better included in the decision process.

Long-Term Economic Planning

The National Fire Management Analysis System (NFMAS) is used by the Forest Service for identifying the most efficient fire protection budget level. The Bureau of Land Management and most of the States also use this system (Brandel 1987).

The NFMAS model considers only initial attack forces on nominally uniformly spreading fires. The process depends upon the development of a probability distribution of estimated sizes for large fires (the probable result given a failure in initial attack). "Presently this distribution must be based on historical fires since there is no objective way to generate a 'future history' based on current and expected fuel, weather, and other conditions that affect fire spread and size in a given area. Since this historic distribution reflects past conditions and large fire suppression actions, not current or future ones, a potential bias is introduced into the analysis." (Chase 1989)

The problem of how to interpret historical fire size data for the NFMAS model application is becoming even more complex with the possibility of escaped prescribed natural fires being included in the data base. A fire growth simulation model would eliminate the need to rely solely on historical fire data to generate the fire size distributions. In addition, a fire growth simulation model would allow the planning process to be expanded to include suppression options at points other than at initial attack.

Urban Wildland Interface

A fire growth simulation model can also be useful in planning at a site-specific level, such as is needed to deal with the urban wildland interface. Model results can be used in setting standards for safe development, planning protection requirements, and communicating with those who are not used to dealing with fire: land owners, developers, land use planners, government administrators, and elected officials.

A fire growth simulation model could be used to evaluate the probability of a fire spreading into a developed area. The behavior of a fire could be simulated under several weather scenarios, cool-wet-and-calm to hot-dry-and-windy. Graphic display of fire spread could project a fire safety message more effectively than words. A simulated fire could dramatically illustrate the effect of fuel treatment around homes and the effect of prescribed fire around a developed area. A fire growth simulation model could help determine specific protection requirements, such as engine placement, and help determine the effect of pre-positioning initial attack forces. It could be used in planning fuel breaks and other pre-attack measures.

One of the more important uses of a fire growth simulation model might be in communication with people who are not used to thinking about fire. Irwin (1987) pointed out the importance of good display in communication: "the diagrams present a 'flat earth' character ... The average citizen, developer, planning commissioner, or elected official cannot grasp any realistic concept of the fire environment from these diagrams. Without that ability, final planning decisions tend to be less than adequate, if not detrimental to fire protection interests."

Summary

It will not be possible to develop a generic fire growth simulation model to satisfy all applications. A successful simulation system must be designed to meet specific needs. Consideration must be given to the source and resolution of the data required to run the simulation, the form of the results, and the interaction with the user.

Although all applications will require weather input, the source and resolution of that information will vary greatly. For example, shift projections on a wildfire require a spot weather forecast that is based on observations taken on site while a long-term planning application will use climatology and "what-if" scenarios.

The form of the output should be suited to the application. In some cases the actual fire location is critical; the user may want to watch a simulation of an hourly progression of fire growth. This level of resolution is unnecessary if the question is whether the fire will cross a critical boundry by the end of the fire season.

A fire growth projection may be for worst-case conditions, or most probable, or a range of values, or a probability distribution. In any case, display will be an integral part of the simulation. Color graphics can communicate information quickly and efficiently whether the result is a single fireline location or probability output.

Some applications need flexibility while others require consistency. A real-time fire growth model designed for use by an expert should be flexible to allow for expert opinion to override the model. On the other hand, an economic planning model should be designed for consistency and repeatability.

An overview of some of the potential applications of a fire growth simulation model is just a first step. It will take additional planning to design the systems for specific applications in the context of the fire behavior/fire danger rating system of the future.

It must be emphasized that in all applications, a fire growth simulation model will be designed to support decisionmaking. A person, not the model, will make the decision.

References

BRANDEL, K.A. 1987. The National fire management analysis system: Flexible tool. Fire Manage. Notes. 49(1): 26-28.

CHAMBERS, J.W. 1985. Using decision trees in escaped fire situation analysis. Fire Manage. Notes. 46(2): 13-15.

CHASE, R.A. 1989. [Electronic communication to P. Andrews]. January 31. 1 leaf. On file at: USDA For. Serv. Intermt. Res. Sta., Intermt. Fire Sci. Lab.

FRANDSEN, W.H., and P.L. ANDREWS. 1979. Fire behavior in nonuniform fuels. USDA For. Serv. Res. Paper INT-232, Intermt. For. and Range Exp. Sta.

IRWIN, R.L. 1987. Local planning considerations for the wildland-structural intermix in the year 2000. P. 38-46 In J. B. Davis and R. E. Martin, tech. coord., Proc.Symp. on Wildland Fire 2000, South Lake Tahoe, CA, Apr. 27-30, 1987, USDA For. Serv. Gen. Tech. Rep. PSW-101, Pacific SW For. and Range Exp. Sta.

KEANE, R.E., S.F. ARNO, and J.K. BROWN. [In press]. Simulating cumulative fire effects in ponderosa pine/Douglas-fir forests. Submitted to Ecology.

KEOWN, L.D. 1985. Fire behavior prediction techniques for park and wilderness fire planning. P. 162-167 In J.E. Lotan, B.M. Kilgore, W.C. Fischer and R.W. Mutch, tech. eds., Proc. Symp. and Workshop on Wilderness Fire, Missoula, MT, Nov. 15-18, 1983, USDA For. Serv. Gen. Tech. Rep. INT-182, Intermt. For. and Range Exp. Sta.

KOURTZ, P., S. NOZAKI, and W. O'REGAN. 1977. Forest fire in the computer- A model to predict the perimeter location of a forest fire. Fisheries and Environment Canada. Inf. Rep. FF-X-65.

LAW, A.M., and W.D. KELTON. 1982. Simulation modeling and analysis. McGraw-Hill Book Co.

LUKENS, D., and J. KREBS. 1987. Long-term fire behavior projections. Fire Manage. Notes. 47(4): 22-23.

ROTHERMEL, R.C. 1972. A mathematical model for predicting fire spread in wildland fuels. USDA For. Serv. Res. Paper INT-115, Intermt. For. and Range Exp. Sta.

ROTHERMEL, R.C. 1983. How to predict the spread and intensity of forest and range fires. USDA For. Serv. Gen. Tech. Rep. INT-143, Intermt. For. and Range Exp. Sta.

ROTHERMEL, R.C., and P.L. ANDREWS. 1987. Fire behavior system for the full range of fire management needs. P. 249-252 In J.B. Davis and R.E. Martin, tech. coord. Proc. Symp. on Wildland Fire 2000, South Lake Tahoe, CA, Apr. 27-30, 1987, USDA For. Serv. Gen. Tech. Rep. PSW-101, Pacific SW For. and Range Exp. Sta.

ROTHERMEL, R.C., D. DESPAIN, R. NORUM, S. HUSARI, R.E. BURGAN, and T. NICHOLS. 1988. Report: fire behavior projections for the Greater Yellowstone Unified Area Command. Unpublished paper on file at: USDA For. Serv. Intermt. Res. Sta., Intermt. Fire Sci. Lab.

USDA/USDI. 1988. Fire management policy review: report concerning fire management policy for National Parks and Wilderness. Memorandum for Secretary of Agriculture/Secretary of the Interior. Unpublished paper on file at: USDA For. Serv. Intermt. Res. Sta., Intermt. Fire Sci. Lab.

VAN GELDER, R.J. 1976. A fire potential assessment model for brush and grass fuels. Fire Manage. Notes. 37(3): 14-16.

VAN WAGTENDONK, J.W. 1985. Fire suppression effects on fuels and succession in short-fire-interval wilderness ecosystems. P. 119-126 In J.E. Lotan, B.M. Kilgore, W.C. Fischer, and R.W. Mutch, tech. eds., Proc. Symp. and Workshop on Wilderness Fire, Missoula, MT, Nov. 15-18, 1983, USDA For. Serv. Gen. Tech. Rep. INT-182, Intermt. For. and Range Exp. Sta.

Development of an Automated Hourly Fire Weather Network and Its Application to Fire Management in British Columbia

S.K. GRIMALDI AND V.E. FLETCHER
Planning, Development, and Research Section
Protection Branch, British Columbia Ministry of Forests
Victoria, B.C.

Abstract

Recent technological developments permit the collection of remote hourly weather observations and their transfer to a mainframe computer via ultra-high frequency (UHF) telemetry and standard telephone lines. Included is an intelligent telephone modem, capable of controlling up to 15 remote weather stations, that acts as a network controller. Weather observations (temperature, relative humidity, wind speed and direction, and precipitation), battery voltage, and date/time information are collected hourly from each station. Up to 96 hourly observations per station can be stored in memory.

After data collection by the network controller has been completed, the mainframe computer initiates a call to transfer the most recent hourly data. Data transfer software on the mainframe includes error-checking routines to ensure data integrity. Weather observations are used to produce hourly fire weather indexes, fire behaviour predictions, and colour graphic output using British Columbia's Advanced Fire Management System (AFMS). These systems are available at 43 district, 6 regional, and 8 branch offices as well as to industry, provincial and national parks, and the Atmospheric Environment Service.

Résumé

Une technologie a été mise au point récemment pour permettre de recueillir des observations météorologiques horaires ebignées et de les transférer à un ordinateur central par émetteur UHF de télémesure et lignes téléphoniques ordinaires. Elle comporte un modem téléphonique électronique capable de contrôler jusqu'à 15 stations météorologiques éloignées. Le modem téléphonique, qui agit comme contrôleur de réseau, recueille les observations météorologiques (température, humidité relative, vitesse et direction du vent, et précipitations), surveille le voltage des accumulateurs et reçoit des informations sur la date/l'heure à chaque heure de chaque station. On peut mettre en mémoire jusqu'à 96 heures d'observations horaires par station.

Lorsque le contrôleur du réseau a terminé la collecte de données, l'ordinateur central lui demande de lui transférer les données horaires les plus récentes. Le logiciel de transfert des données à l'ordinateur central comprend des sous-programmes de correction d'erreurs pour s'assurer de l'intégrité des données. Les observations météorologiques horaires servent à établir des indices forêt-météo horaires et les prévisions du comportement du feu et à produire des graphiques en couleurs à l'aide du système perfectionné de gestion des incendies de la Colombie-Britannique. Ces systèmes sont opérationnels dans 43 districts, 6 régions et 8 bureaux de directions ainsi qu'à l'industrie aux services provincial et national des parcs et au Service de l'environnement atmosphérique.

Introduction

Since the early 1970's, the British Columbia Ministry of Forests has maintained a network of 202 weather stations throughout the province. These stations are complemented by 40 Atmospheric Environment Service (AES) airport stations. The stations collect daily 1200 hours Local Standard Time (LST) weather observations (temperature, relative humidity, wind direction and speed, and 24 hour accumulated precipitation) required to calculate components of the Canadian Fire Forest Weather Index System. Weather stations and their instrumentation have ranged from rudimentary psychrometers, mechanical anemometers, and "coffee can" rain gauges to sophisticated microcomputer-based weather recorders using ultra-high frequency (UHF) telemetry.

The present Canadian Forest Fire Weather Index System accounts for differences in diurnal variation throughout the province. Using one 1200 hours LST observation from each weather station and the same diurnal adjustment, the indexes are projected to the peak daily burning time (approximately 1600 hours). No seasonal, latitudinal, or topographical adjustments are taken into consideration.

The need for timely and accurate weather data for fire managers to use in planning, operations, and prescribed burning has increased. With the introduction of the Advanced Fire Management system (AFMS) to

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

regional and district offices, the need for hourly weather data has become a key component in fire management decision making.

The British Columbia Ministry of Forests and two B.C. companies, Forest Technology Systems (FTS) and ND Systems Ltd., have developed technology which will collect hourly weather data from remote stations and transports this information to a mainframe computer using UHF telemetry and telephone lines. The equipment uses frequencies assigned for weather data collection in the UHF spectrum (401 to 406 MHz) allocated by the Federal Department of Communications for meteorological data. The use of UHF frequencies frees the Ministry of Forests' VHF radio network for unimpeded voice communications.

System Description

Hourly weather observations collected by the Provincial Weather Station Network are transferred to a central mainframe (VAX 8800) computer via standard dial up telephone lines (provincial PROVNET network) and dedicated radio links where necessary. The most remote weather stations are solar-powered, and equipped with FTS UHF telemetry transceivers and weather station equipment.

The transceivers are in radio contact with a companion UHF telemetry transceiver at the "base" with power and telephone services. Additional transceivers may be required to serve as "store and forward" repeaters to bring certain remote stations within radio contact of the base station by relaying data between weather stations. A TM4000CD intelligent telephone modem polls, on the hour, the network of radio transceivers and weather stations, storing the most recent weather data for immediate delivery to the mainframe.

Figure 1 shows a TM4000CD modem collecting weather data from two remote weather stations. The mainframe dials out to each TM4000CD network controller and requests the transmission of weather observations collected by the remote weather stations for the network cluster controlled.

Once an hour (at 20 minutes after the hour) the mainframe collects and stores information from each weather station. The weather data are then processed to determine weather and fire danger indexes. The software dates and time stamps each observation, records the battery voltage from each remote weather station and automatically logs any problems to a message file.

The TM4000CD also stores the most current 96 hours of weather data for each weather station under its control. This provides the capability for re-accessing data in the event of telephone line failure or routine maintenance to any component. Up to 500 weather stations can be managed by the mainframe software, on a 24 hour basis.

The Ministry of Forests contracted FTS to redesign their original telephone modem to allow hourly collection of data from remote weather stations. The redesign included a real time clock, continuous-duty internal power supply, incoming call lockout, and a completely rewritten software package to automatically collect weather data on an hourly basis.

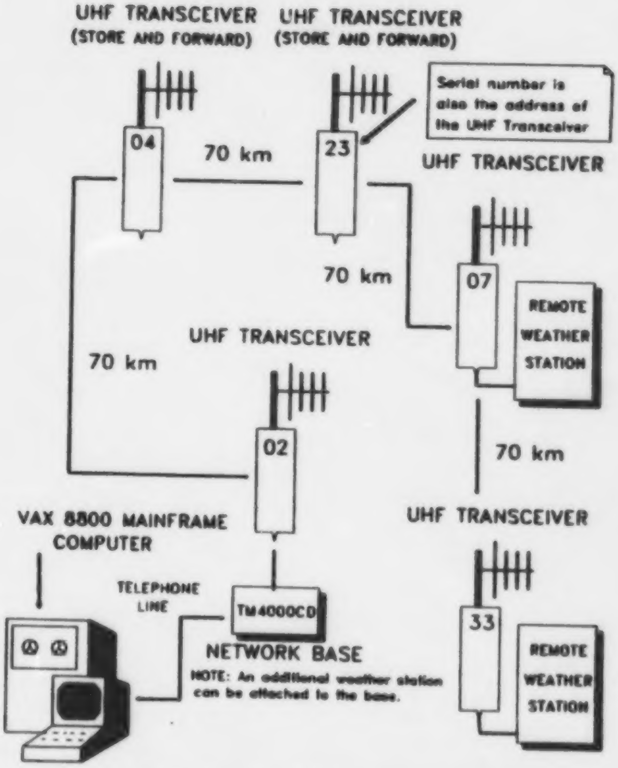


FIG 1. Typical network format of a TM4000CD modem collecting weather data from a cluster of "store and forward" repeaters and remote weather stations.

The TM4000CD contains a standard 300/1200 baud asynchronous telephone modem conforming to the Bell 212A standard for use on dial up telephone lines. It is attached to a simple microprocessor based controller board manufactured by FTS. The controller board provides Random Access Memory (RAM) for storing the retrieved weather data, and Read Only Memory (ROM) for the program which controls operation of the network of remote stations and communications to the mainframe.

The mainframe computer software contains an electronic log of system messages to facilitate system management and troubleshooting. Each call to a TM4000CD is logged into the messages file with all associated messages. There are two types of messages contained in the message file - mainframe software messages and the TM4000CD and weather station hardware/software messages. The mainframe software messages provide information on date/time, modem responses, Input/Output request, and weather data. The TM4000CD messages contain information on weather station date/time, telemetry polling, and battery voltage of the remote station.

Integration with Protection Computer Systems

Hourly weather observations form part of the fire weather system which is a large database of weather data and weather index calculations dating back to 1970. The system provides the ability to forecast fire weather indexes used to rate fire danger and report on the database. Two types of programs are available on the system, one for data summaries, the other for data analysis. The former reports either current year or historical yearly summaries for one station (all days) or for all stations (one day). Each report contains fire indexes, 1200 LST weather observations, drought code analyses, and fire behaviour analyses. The data analysis programs permit the user to examine historical fire weather prescriptions. There are also programs to plot drought codes and weather station locations on graphics plotters.

The Ministry of Forests responded to the need for better weather information through the development and implementation of a hardware and software system known as the Advanced Fire Management System (AFMS).

The AFMS system is graphic-oriented and designed for use on a colour graphics terminal. The AFMS allows the user (through a pull-down menu system) to choose options and display parameters that will in turn display colour-coded maps of the entered options and parameters.

The AFMS weather data maps can be displayed by province, region, or district. The main menu options include display, lightning, fire behaviour, fire prediction, data entry, fuels data, property assessment, and timber values besides weather observations and indexes. Future projects such as meso-scale wind and fire growth models will also be incorporated into the automated hourly weather network for weather observations.

Presently there are 45 weather stations operating with this new technology in British Columbia. An additional 26 stations will be installed this year. The remaining 103 stations be upgraded to the hourly weather network over the next three years. These data are made available to over 70 users -including the B.C. Ministries of Forests, Environment, and Parks; the Atmospheric Environment Service; Forestry Canada; Parks Canada; and numerous forest industry offices.

References

CANADIAN FORESTRY SERVICE. 1984. Tables for the Canadian Forest Fire Weather Index System. Environ. Can. For. Ser. Tech. Rep. 25 (4th ed.).

GRIMALDI, S.K. 1987. Provincial remote automated weather network, a prototype project report. Internal Rep., B.C. Min. of For., Protection Branch, Victoria B.C.

HOLROYD, S. 1987. Protection Branch automated weather link (AWL) user manual. ND System Limited, Victoria, B.C.

WALKINS, D. 1987. TM4000CD intelligent telephone modem. Forest Technology Systems Limited, Victoria, B.C.

Protection des forêts contre le feu en Bulgarie
Rendre les forêts moins combustibles

Y. KURPANOV
Expert Forestier
AFIF-LESCOMPLEKT-FAO
Sofia, Bulgarie

I. Règles d'aménagement et de sylviculture

Les forêts en République Populaire de Bulgarie sont propriété nationale (publique). Il n'y a pas de forêts privées. Une toute petite surface est mise à la disposition des fermes coopératives et des complexes agro-industriels pour satisfaire certains de leurs besoins économiques (domestiques), de bois de chauffage et de bois d'oeuvre.

De même une pas très grande partie de ces forêts est distinée aux pâturages forestiers où nous réalisons parfois des coupes d'éclaircie - là où l'érosion manque ou bien est minime.

Les problèmes normatifs concernant la protection des forêts contre les incendies et l'allumage sont réglés d'après l'article 55 du Code Forestier. Cette obligation est concrétisée également dans le chapitre VIII des Réglements de la mise en pratique du Code Forestier. En exécution de ces obligations et des Directives pour l'aménagement anti-incendies dans toutes les entreprises forestières (soit d'exploitation et de reboisement) dès la formation des projets d'aménagement forestier on élabore une partie pour l'aménagement anti-incendies consernant le fonds forestier d'Etat intégral. Dans ces projets, séparément pour chacune des enterpirse forestières, on rédige des chapitres spéciaux de défense anti-incendiaire, ainsi que pour la lutte totale contre les insectes et les champignons nuisibles, contre les chablis etc....On dresse également une carte forestière particulière consernant les dispositions anti-incendies ainsi que le degré de combustibilité pour chacune des séries forestières et pour tous les bassins versants.

Dans l'exercice des documents mentionés ci-dessus et des dispositions communes pour l'augmentation de la protection anti-incendies et de son efficacité on élabore des plans quinquennaux et à partier d'euse d'eux on fait des plans annuels pour la défense anti-incendiaire.

D'après les analyses approfondies faites durant les années précédentes sur l'état de l'activité concernant la protection des forêts contre les incendies et les allumages, sont désignées et sont accomplies les dispositions indispensables et plus importantes qui, pour l'année 1987 par exemple, donnent les résultats suivants:

1. Déclarées et marquées sur le terrain les surfaces forestières ménacées par le feu:	1 186 769 ha
2. Minéralisées (creusées) des bandes de terre dans les plantations forestières:	282 km
3. Coupage de percées forestières anti-incendiaires:	233 km
4. Entretien de bandes de terre anciennement creusées:	1518 km
5. Nettoyage de bande le long des chemins de fer, des routes principales et des autostrades:	1014 km
6. Elaboration des objets de démonstration avec des contenus anti-incendiaires - nombre:	1710
7. Des signaux-avertisseurs mis sur le terrain - nombre:	4860
8. Des tracts imprimés et distribués:	15000
9. Appels par la Radio-télévisé locale:	500
10. Appels par la Radio-Télévision nationale:	5
11. Jumelles de surveillance achetées:	41
12. Extincteurs portatifs:	230
13. Réservoirs d'eau construits anti-incendies:	19
14. Observateurs anti-incendies nommés:	544
15. Tours-observatoires construites anti-incendies:	115

En été 1987 le pâturage pour le petit bétail a été permis dans les régions ménacées de feu lors que dans les régions où le pâturage ne pouvait pas être permis on a fauché toutes les herbes et on en a fait du foin.

Au cours des travaux pour l'accomplissement des dispositions mentionnées ci-dessus pour conjurer les incendies forestiers durant la même année ont été dépensés 1 419 370 lévas = 1 710 000 dollars EU.

Par suite des périodes sèches et chaudes durant les quelques dernières années les plantes herbacées sèches augmentaient le danger et les risques d'éclosion de feu. Les sources principales de feu dans les plantations résineuses sont également les déchets de coupes d'éclaircies. Ils sont facilement enflammables soit par négligences soit par les visiteurs accidentels dans la forêt - touristes, villégiateurs, moyens de transport traversants et autres. Cela est évident par les nombres des incendies causés pendant la même année:

Présenté au 10ième Congrès sur les incendies et la météorologie Forestière les 17 au 24 avril, 1989 à Ottawa, Canada.

a. Par négligence	55
b. Par l'activité rurale lors du déchaumage des champs par brûlage	15
c. D'éclairs (foudres)	6
d. D'autres (inflammation spontanée)	5

Les surfaces atteintes sont avant tout dans les plantations résineuses. De toutes les forêts incendiées en 1987 = 301 ha, la surface des plantlations résineuses s'élève à 255,5 ha et des feuillues - 45,5 ha.

En pour-centage de leur âge elles sont en proportions suivantes:

a. Plantations jusqu'à 10 ans	71%
b. Plantations de 10 à 20 ans	23%
c. Plantations au dessus de 20 ans	6%

Durant les derniers dix ans (avant 1987) moyennement annuellement les surfaces forestières incendiées sont comme suit:

a. Incendies surgis - nombre	98
b. Surface incendiée	305 ha
résineuses	202 ha
feuillues	103 ha
c. Dégats en lévas	290 500

En examinant les années d'avant 40-50 ans, les incendies dans les forêts de la Bulgarie étaient un vrai désastre (dans les cadres de quelques milliers d'ha par an). D'après les données ci-dessus on peut remarquer qu'à cet égard la République Populaire de Bulgarie a atteint un succès très important. En outre des dispositions mentionnées, pour ce succès contribuent également certaines dispositions complémentaires comme suit:

1. En outre des dispositions prévues dans les projets d'aménagement forestier, les gérants des entreprises forestières (tenant compte des changements causés par les chablis, par exemple), ensemble avec le service local des pompiers examinent chaque année tous les districts anti-incendies et donnent des dispositions anti-incendiaires complémentaires.

2. Pendant les coupes d'éclaircie l'on écarte en même temps toutes les causes d'éclosion de feu et d'allumage (matériaux enflammables). On fait des débroussaillements manuels et mécaniques et dans les plantations résineuses on cultive des champs de blé et des prés pour nourrir le gibier d'une part, et d'autre part - dans un but anti-incendies.

3. On nettoie à fond les terrains forestiers (les plantations) de tous matériaux enflammables pouvant causer l'éclosion de feu (cigarettes et allumettes jetées).

4. On met complémentairement des signaux-avertisseurs et des écriteaux indicateurs interdisant le passage dans les régions ménacées.

5. On fait une inspection fondamentale de l'état de tous les instruments anti-incendies. On renforce également la discipline des groupes pour l'extinction des incendies qui sont (les groupes) de 8 à 10 pour chacune des entreprises forestières composés de 5 à 20 personnes pour chacun des groupes. Si cela s'impose, les groupes pourraient être équipés de matériaux complémentaires lors de l'extinction du feu éventuellement surgi.

6. On organise des services de jour et de nuit avec l'aide des hommes de la région en mettant à leur disposition des moyens de transport afin d'organiser la surveillance, la signalisation opportune et rapide pour la découverte et l'étouffement du feu.

7. Les entreprises forestières, sachant que durant les périodes ménacées par les incendies, les facteurs subjectifs jouant un rôle important, limitent les passages dans les régions ménacées. Cette limite se fait grâce à une large publicité parmi la population locale et parmi les touristes éventuels à l'aide d'écriteaux, de tableux et aussi de signaux-avertisseurs complémentaires.

8. On rédige un programme détaillé quotidien de surveillance et pour attirer des volontaires parmi les écoliers et les habitants locaux d'après des conditions concrètes. D'après ces conditions on pourrait organiser des instructions complémentaires.

9. Pour la protection des forêts des incendies un film spécial a été préparé et projété.

10. On examine annuellement les avions et les hélicoptères de l'aviation civile bulgare ainsi que l'aviation au service de l'agriculture pour leur empressement lors du transport des groupes d'étouffement du feu et des instruments là où il n'y a pas d'autres moyens de transport. On entretien également des liaisons permanentes radio-téléphoniques avec les Centres. Et dans les cas échéants on fait le nécessaire.

II. Critères de danger

Indépendamment du fait que la République Populaire de bulgarie est un pays touristique visité annuellement par plusieurs millions de touristes, grâce aux dispositions mentionnées ci-dessus les incendies dans les forêts sont un évènement relativement rare. Un élément favorable contre les incendies et les allumages est également le terrain fortement accidenté dans les régions montagneuses - des rivières et des ravines profondes, des ruisseaux et des torrents escarpés, de grandes clairières et des pâtis, de larges routes et autostrades, même des pistes pédestres. Durant les derniers quelques ans il n'y a pas eu d'incendies enrégistrés plus grands que 20-25 ha. En outre chacun des incendies surgis est étouffé relativement vite.

Pour cette raison dans notre pays il n'a pas été indispensable de provoquer des feux tactiques et contre-feu pour conjourer des incendies déjà éclatés de dimensions énormes.

NB: Pour cette raison nous ne possédons pas d'avion-canadairs pour éteindre de grands incendies.

Technology Transfer in Saskatchewan: Operational Use of the Canadian Forest Fire Danger Rating System

W.J. DE GROOT
Forestry Canada, Northwest Region
Prince Albert, Saskatchewan

Abstract

In 1985, Forestry Canada and the Saskatchewan Department of Parks, Recreation and Culture initiated a technology transfer program in fire management under a federal-provincial forestry agreement. A main goal of this program was to deliver recent research and development information on the Canadian Forest Fire Danger Rating System (CFFDRS) to the field level. In this case, the technology transfer process had three phases. Firstly, field staff were made aware of the capabilities of the CFFDRS through information sessions. Next, training courses were developed to instruct in the use of the CFFDRS. This was done through case studies which utilized historical information from Saskatchewan wildfires. The final step was to demonstrate its application in the field during actual campaign fire situations. These steps eventually led to the implementation of a provincial Fire Suppression Preparedness System based on the CFFDRS. This paper provides an overview of the technology transfer activities during the period 1985-1989 which resulted in the operational use of the CFFDRS.

Résumé

En 1985, le Service canadien des forêts et le ministère des Parcs, des Loisirs et de la Culture de Saskatchewan entreprenaient un programme de transfert de la technologie en matière de gestion des incendies de forêt dans le cadre d'une entente fédérale-provinciale de foresterie. L'objectif de ce programme était de fournir l'information sur les résultats de recherche et développement récents sur la Méthode canadienne d'évaluation des dangers d'incendie de forêt (MCEDIF) au niveau des opérations. Dans le cas présent, le processus de transfert technologique comportait trois étapes. La première consistait à informer le personnel dévoué aux opérations des capacités de la MCEDIF grâce à des séances spécialement conçues à cette fin. La deuxième étape prévoyait l'élaboration de cours de formation sur l'utilisation de la MCEDIF. Les cours présentant des études de cas fondées sur des données historiques sur des feux de friches survenus en Saskatchewan. La dernière étape consistait à démontrer son application aux opérations lors de véritables incendies de forêt. Ces étapes ont éventuellement menées à la mise en oeuvre du systéme provincial de mise en alerte de la suppression du feu basé sur la MCEDIF. Le présent article décrit les activités du programme de transfert technologique durant la période 1985-1989 qui ont amenée l'utilisation opérationnelle de la MCEDIF.

Introduction

In 1984, the province of Saskatchewan (Dept. of Parks, Recreation and Culture) and the Canadian federal government (Forestry Canada) entered into a five-year Forest Resource Development Agreement (FRDA). A primary objective under the FRDA was to assist in the maintenance of timber supplies, which included a program of enhanced forest protection (Anon. 1984). The fire management component of this program included the upgrading of the provincial fire weather station network (with remote automatic weather stations) and the lightning locator system (i.e., additional direction finders). However, the major effort to enhance fire management capabilities under the FRDA was in technology transfer.

In the prairie provinces, research and development has historically been the primary focus of the federal forestry service fire research group at Edmonton, Alberta (Alexander and McAlpine 1989). Although a few studies in Saskatchewan were aimed at research applications[1] (Ogilvie 1989), technology transfer activities in fire research/management were not undertaken in Saskatchewan on a full-time basis prior to the FRDA. The need for technology transfer was reflected by a lack of use of the Canadian Forest Fire Danger Rating System (CFFDRS) (Canadian Forestry Service 1987, Stocks et al. 1989) in the daily decision-making process. In particular, general field knowledge and use of the Canadian Forest Fire Weather Index (FWI) System (a sub-system of the CFFDRS) was minimal, at best. This was despite the fact that the FWI System was operationally useable since 1970, and that a tremendous amount of research and development had gone into the CFFDRS[2]. Therefore, it was decided that the FRDA would be used as a vehicle to transfer CFFDRS research and development to the managerial and field levels of Saskatchewan's fire management organization.

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

The Technology Transfer Plan

The most critical step in technology transfer is the first one - planning (Marx 1986). In this case, technology transfer was to be completed using three phases. Firstly, field staff (and managers) needed to be informed on the capabilities of the CFFDRS. Secondly, they were to be shown how this system could be integrated into their daily operations to make tasks easier or decisions/results more accurate. This phase required instruction in the use of the CFFDRS. The final phase was to take this new technology into the field, and into management operations, and demonstrate its use in actual working situations. Documentation of this technology for operational (as opposed to research) use was done during each of these phases. This technology transfer plan is quite similar to that described by Blatchford (1972) as being required for effective transmission of information - i.e., conversation, demonstration, participation, and publication. The approach taken in this plan follows a technology marketing situation, or 'supply-push' (Callaham 1984, Cayford and Riley 1986). This approach is used when technology is available and the information is not in immediate demand. This is not an indication that the CFFDRS, or fire danger rating in general, is of no use to the user. However, it clearly points out to researchers that user groups are not necessarily well-informed about research products and their capabilities. It was believed that with promotion of the CFFDRS, this would turn into a 'demand-pull' situation where its application would be requested in order to solve current problems. The problem-solving approach has virtually the same steps as the product-marketing approach, except that the impetus comes from technology demand (Callaham 1984). The problem-solving situation is much more desireable since acceptance of new technology and committment to change is much easier. The strategy for this technology transfer plan was to change a 'supply-push' situation into 'demand-pull' so that the program would eventually be driven by the value of the product.

Technology Transfer Activities

PHASE I - INFORMATION SESSIONS

The initial step towards informing management and field staff of the CFFDRS and its capabilities, was to travel to each of the regions. Discussions with operational people provided information on daily procedures, management and field suppression needs, the exact level of understanding of the CFFDRS, and most importantly - attitudes. There wasn't a great deal of difference between the regions (and the provincial fire centre) on any of these topics. The province operates a de-centralized fire management system with only staff at the provincial fire centre being committed to fire operations on a full-time basis. The FWI System (Van Wagner 1987) component values were received by the regional fire centres, but seen of little value and not understood. There was no knowledge of the Canadian Forest Fire Behavior Prediction (FBP) System (Lawson et al. 1985), another sub-system of the CFFDRS. Decisions were made almost entirely on past experience. There was great need for a time-saving device that would simplify regional fire operations, as most staff had other duties to perform. However, there was skepticism about the abilities of the FWI and FBP Systems to fill this need. For most people, this was the first time they had met anyone from the fire research community.

Although the situation didn't seem too promising, it provided a starting point. The fact that fire researchers actually travelled to the field to ask questions and find out needs added credibility to technology transfer efforts, and made acceptance a little easier to gain. Obviously, if this was to become a 'demand-pull' situation, the needs of management and field staff would be the focus.

As previously mentioned, time constraints were perceived as being a major problem in operations. Providing a simple decision-aid, such as the FWI or CFFDRS System, could solve this problem. Most importantly, this decision-aid could address a more serious problem: lack of a formalized decision-making process, or decision by pure judgement. Operations were being run by staff with 20-30 years experience who were able to retire in a short period of time. Extensive fire experience beyond this small group of managers was extremely limited. Use of a formalized decision-aid system would allow new staff to fill key roles, and it would also ensure that experienced managers could properly evaluate burning conditions through the use of a common, unbiased measuring stick. Obviously, those people with more experience would be able to use this decision-aid more effectively.

Formal and informal information sessions were provided at every opportunity. The information being supplied was not dealt with in a purely technical sense for fear it would be rejected because of its complexity. Rather, it was presented in a simple theoretical way using basic examples. Again, the key approach being used was showing how it filled their needs. Something which wasn't directly identified by operations staff, was the need for a method of justifying presuppression resource levels. There was concern about the disparity in amount and distribution of resources during the fire season. A formal system for assessing burning conditions across the province provided the means of distributing resources. Although this wasn't a clearly identified need, it was important for jurisdictional strength and autonomy in this de-centralized system. This need was used to its fullest potential in creating a 'demand-pull' situation.

Information sessions were used to deliver this message, and they were presented at regional locations whenever possible. These sessions took the form of seminars, committees, formal and informal meetings, introductory presentations at courses, and a lot of adhoc personal contact. This phase continued simultaneously with the other phases throughout the five-year period of the FRDA.

PHASE II - COURSE INSTRUCTION

The primary goal of the first phase was to create interest and gain a commitment to further examine use of the CFFDRS. For the second phase to be successful, it had to be presented using practical examples of everday operations. A thorough understanding of fire operations at the field, district, regional, and provincial levels was required in order to present this phase with any credibility. This understanding was gained by going to these locations to discuss operations, or by directly participating in operations.

Instruction on the FWI and FBP Systems was given by the author who was employed as a fire research officer working under the FRDA. Courses were generally 1-2 days long, and utilized a workshop approach as much as possible in order to give students 'hands-on' experience in doing calculations and making decisions. A certain amount of theory was necessary, but it was kept to a minimum and presented early in the course. Students were also given practical training on computers using various software programs dealing with the CFFDRS[3] (McAlpine 1987).

There were a number of publications produced during the FRDA which served as excellant training aids during courses. A color poster illustrating fire behavior in relation to the FWI System (Alexander and De Groot 1988) proved popular with course participants (Alexander et al. 1989). As well, a poster illustrating FBP System fuel types (De Groot 1987a) and the Fire Growth Calculator (McAlpine 1986) assisted with instruction on the FBP System.

Over the course of the FRDA, a total of 19 instructional courses were presented in Saskatchewan (Anon. 1988). Classes generally had 15-30 people in attendance (Table 1), with every district and region eventually being represented. Credibility and acceptance of the CFFDRS grew considerably as Phase II proceeded.

PHASE III - FIELD USE

Up until this point, technology transfer had taken a theoretical approach. Specific examples of CFFDRS applications were based on historical situations where hindsight was always 20/20. Final acceptance would not be achieved until its usefulness could be proven in real-time. Perfect application was never expected at the first attempt because of an operational 'learning-curve'. However, this was overcome in a short period of time. During the final year of the original FRDA, an opportunity occurred which provided for the secondment of the author to the provincial fire management organization. This allowed the province to utilize the Forestry Canada employee as a fire behavior officer (a previously non-existent position) on campaign wildfires, and to assist duty officers at the provincial and regional fire centres. This situation enhanced technology transfer efforts, and accelerated the process.

Table 1. Summary of CFFDRS course presentations given in Saskatchewan during 1985-1989.

Date	Location	Course/Session Title	Number of Attendees
Nov. 29, 1985	Kelsey Institute, Saskatoon	FWI System	25
Jan. 14, 1986	Prince Albert	FWI System	16
Jan. 21, 1986	Prince Albert	FWI System	16
Feb. 12, 1986	Prince Albert	FWI and FBP Systems	15
Feb. 19, 1986	Prince Albert	FWI and FBP Systems	16
Mar. 13, 1986	Kelsey Institute, Saskatoon	FBP System	25
Apr. 16, 1986	Prince Albert	FWI and FBP Systems	30
Jan. 15, 1987	Prince Albert	FWI, FBP Systems and Fire Growth Calculator	23
Jan. 22, 1987	Prince Albert	FWI, FBP Systems and Fire Growth Calculator	25
Feb. 5, 1987	Prince Albert	FWI, FBP Systems and Fire Growth Calculator	30
Oct. 20, 1987	Northern Institute of Technology, Prince Albert	FWI, FBP Systems and Fire Growth Calculator	25
Mar. 3, 1988	Prince Albert	FWI, FBP Systems and Fire Growth Calculator	18
Mar. 10, 1988	Prince Albert	FWI, FBP Systems and Fire Growth Calculator	23
Apr. 26, 1988	Melville	FWI, FBP Systems and Fire Growth Calculator	22
May 4, 1988	Prince Albert	FWI System	15
Feb. 13, 1989	Prince Albert	FWI and FBP Systems	15
Feb. 20, 1989	Prince Albert	FWI and FBP Systems	17
Mar. 9, 1989	Prince Albert	FWI, FBP Systems and Fire Growth Calculator	22
Apr. 7, 1989	Prince Albert	FWI and FBP Systems	15

As a fire behavior officer, the author was supplied with a portable fire weather station, and a battery operated lap-top computer (with various CFFDRS software) and printer. This allowed the author to make hourly fire behavior predictions using the CFFDRS and site-specific weather information. The first opportunity to make fire spread predictions under an actual field situation was in 1987 when the Elan fire grew to 70 000 ha during a 30-hour period. Although this fire amassed most of its final size during a relatively short time interval, it provided the opportunity to prove that fire spread could be predicted with a fair degree of accuracy by using the CFFDRS[7]. After this point, 'demand-pull' drove the technology transfer program.

The 1987 and 1988 fire seasons were record-setting years for Saskatchewan. As the value of CFFDRS information became apparent, there were constant requests for the assistance of the author in the fire behavior officer role at campaign fires. The largest fire of 1988 was the Coffee fire (32 000 ha). Its major run (25 km) was predicted hours before it started, and the forward spread distance was predicted within 6% of the actual spread. This information was used to plan suppression strategy, and for safety and evacuation considerations for firefighters and the general public. The CFFDRS was also used on this fire to plan the location and timing of backfire operations. A provincial review of the Coffee Fire concluded that the province requires a fire behavior specialist on staff to provide CFFDRS information and predictions.

PROVINCIAL PREPAREDNESS SYSTEM

Following the 1988 fire season, field use and application of the CFFDRS was accepted. However, application to management operations was still somewhat limited. The basics of the FWI System were well-understood and it was constantly used by duty officers for deploying resources. This was a considerable change from before, but the planning power of the FBP System was not being used to its fullest extent.

This led to development of Saskatchewan's Fire Suppression Preparedness System[8]. This system utilizes the FWI and FBP Systems to plan resource levels and deployment in anticipation of burning conditions. It uses forecast FWI System values and determines attack time requirements based on predicted head fire spread rates and frontal fire intensity. Again, acceptance was limited during the initial stages of development, but quickly grew once input from management and field operations staff was solicited. Also, a retrospective review of the 1988 fire season showed that additional helicopters were not hired until after several major fires had become established. This system provides for increases in helicopter levels prior to the onset of serious burning conditions (and fire starts to a certain extent). Once this was explained, 'demand-pull' quickly followed.

Although this system was not an original goal of the technology transfer program, secondment provided the opportunity to develop it. It will be used for the first time during the 1989 fire season, and an operational 'learning-curve' is expected.

Discussion

Reviews of other technology transfer programs show similar results and conclusions (e.g., Cayford and Riley 1986, Kill et al. 1986). There are a number of key points which seem to be universal to successful technology transfer programs. Credibility is often first and foremost on the list of requirements. In a 'supply-push' situation, the research community is required to prove the value (or credibility) of the product. A survey in Cayford and Riley (1986) shows that the most effective technology transfer approach is through field demonstration so that results can be convincingly shown. In this case, all information sessions, demonstrations and courses were aimed at integrating the CFFDRS into management and field operations. This was done to remove any suspicion of application problems and usefulness. Showing how it benefited operations fostered a shift towards a 'demand-pull' situation which made its credibility easier to accept.

Along these same lines, personal contact and communications are critical for success. This creates credibility and is the key to acceptance of the product. Moeller and Seal (1984) have prepared a list of recommendations for improving technology transfer in forestry. Communication between researchers and operational people is the most prevalent requirement on the list. Better communication was facilitated under this program by designating a 'linker', or liaison, between research and operations.

Even though a technology transfer plan is is place, it is also important to be flexible (Kill et al. 1986). Every technology transfer situation is different, so adjustments must be made from the original plan as circumstances dictate. As well, opportunities arise which require deviation from the original plan. In this case, secondment of the author to the provincial fire centre offered an opportunity to increase personal contact (and therefore, credibility and acceptance) with the user group. This increased communication lead to an acceleration of the technology transfer process, as well as a 'demand-pull' for a provincial preparedness system. Interchanging staff was another key recommendation by Moeller and Seal (1984).

Finally, proper publication of technology is also important for success. Research papers are seldom read by user groups (Blatchford 1972 Cayford and Riley 1986), although the information is still in demand. This technology transfer program recognized the need to produce operational-level technology publications, and attempted to do so whenever possible.

Technology transfer also has a few dangers. One is that research participants may become too engrossed in field application. The user agency becomes comfortable with this situation, and the result is that research turns into a service organization working for operations. The same could happen in reverse, with a member of the user agency becoming too involved with the science of the information and neglecting practical field applications. To avoid this, both parties should understand the goal and set a reasonable timetable to achieve it.

The necessity for this program stemmed from an acknowledged lack of direct, formal communication between federal research and provincial operations. There are numerous forums where these two groups meet to discuss fire management problems and possible avenues of research. However, it seems that completed research products do not always make it to the field (or office) where they were intended. If transfer to these levels is to occur, it is the responsibility of the federal fire research group to present and explain these products to client agencies, while these agencies are responsible for operational implementation. In this case, a backlog of incomplete transfer of the CFFDRS necessitated a program which assumed both these responsibilities.

Complete transfer of current CFFDRS information will occur by the end of 1989, and at that time the provincial and federal organizations will resume their regular roles in technology transfer.

There is no doubt that having a fire research officer position in Saskatchewan facilitated the success of this program. Prior to 1985, fire researchers made considerable effort towards transferring CFFDRS technology in Saskatchewan, but it still required a full-time liaison or 'linker' in close proximity to provincial operations to assist and follow-up on new information. This liaison position is the most important key to successful technology transfer. It makes no difference whether this position is provincial or federal. However, it is in the best interests of the user agency to provide a liaison because it is the user's forest that is burning. As well, federal funding of fire-related liaison positions has historically been unsure. The results and success of this program show the critical importance of technology transfer. Commitment of a full-time research/operations liaison is a small price for the user agency to pay when the enormous benefits of science and technology can be gained.

Conclusion

There were a number of reasons for the success of this three-phased technology transfer program including planning, credibility, proper publication, program flexibility, and a lot of communication with the user group. However, the two key factors to the success of this program were establishing a 'linker', and identifying user needs. Change is often difficult to achieve because of loyalty to traditional practices, and a belief in the adequacy of current procedures. Therefore, it may be difficult to prove a need for new technology. Sutton (1986) believes that acceptance of new technology is highly dependent on the perception of risk. He states that successful technology transfer can only be achieved when researchers use a strategy to show that the risks of not adopting a new technology are greater than of those of adopting it. Regardless of the approach taken, the information can't be transferred without a thorough understanding of the user's situation.

Acknowledgments

Technology transfer requires the assistance of many people from all the agencies involved. From Forestry Canada, R. McAlpine and K. Hirsch (Fire Research Officers) provided invaluable assistance as instructors on the various training courses; M. Alexander (Fire Research Officer) contributed considerable time, effort and ideas towards the general development of the technology transfer program. From Saskatchewan Parks, Recreation and Culture, G. Conacher (Operations Manager, Forest Fire Management Branch) and G. Rolles (Director, Northern Field Services) constantly provided the opportunity to present technology transfer sessions and demonstrations to field and management staff; N. Hook (Comm. and Technical Services Manager, Forest Fire Management Branch) and D. Campbell (Training Officer, Forest Fire Management Branch) provided considerable expertise and assistance during the training sessions; R. Duncan (Director, La Ronge Region) and M. Campbell (Bird-Dog Officer) played key roles in the development and implementation of the Saskatchewan Fire Suppression Preparedness System; A.J. MacAuley (Director, Prince Albert Region) supported the technology transfer program through suggestions and ideas resulting from his previous experience as Director of Fire Control. There are dozens of others who assisted in this program, but it is not possible to acknowledge all of them.

---

[1] Ogilvie, C.J. 1985. Evaluation of the Saskatchewan forest fire lookout system. Canadian Forestry Service, Northern Forestry Centre, Edmonton, AB. Study NOR-5-02 File Report No. 4.

[2] Alexander, M.E. 1988. Bibliography on the Canadian Forest Fire Danger Rating System: 1969-1985 (with 1986 and 1987 supplements). Canadian Forestry Service, Northern Forestry Centre, Edmonton, AB. Study NOR-5-05 File Report No. 12.

[3] An unpublished FWI-PC program was developed and provided by B.S. Lee, Fire Research Officer, Forestry Canada, Northern Forestry Centre, Edmonton, AB. Actual case studies of Saskatchewan fires were used to illustrate application of the CFFDRS. Additional publications on the CFFDRS were also produced which dealt with operational situations[6] (De Groot 1987b, 1988a, 1988b). These publications were all written with the operational-level audience in mind.

[4] De Groot, W.J., and Alexander, M.E. 1986. Wildfire behavior on the Canadian Shield: a case study of the 1980 Chachukew Fire, east-central Saskatchewan. In Proceedings of the third Central Region Fire Weather Committee scientific and technical seminar. Edited by M.E. Alexander. Canadian Forestry Service, Northern Forestry Centre, Edmonton, AB. Study NOR-5-05 File Report No. 16. pp. 23-45.

[5] De Groot, W.J. 1989. Fire behavior on the 1987 Elan Fire, Saskatchewan. In Proceedings of the fifth Central Region Fire Weather Committee scientific and technical seminar. Edited by W.J. De Groot. Forestry Canada, Saskatchewan District Office, Prince Albert, SK. Study NOR-36-03-4 File Report No. 1. pp. 26-40.

[6] De Groot, W.J. 1988. Interpreting the Canadian Forest Fire Weather Index (FWI) System. In Proceedings of the fourth Central Region Fire Weather Committee scientific and technical seminar. Edited by K.G. Hirsch. Canadian Forestry Service, Manitoba District Office, Winnipeg, MB. Study NOR-36-03-1 File Report No. 3. pp. 3-14.

[7] De Groot, W.J. 1989. Fire behavior on the 1987 Elan Fire, Saskatchewan. In Proceedings of the fifth Central Region Fire Weather Committee scientific and technical seminar. Edited by W.J. De Groot. Forestry Canada, Saskatchewan District Office, Prince Albert, SK. Study NOR-36-03-4 File Report No. 1. pp. 26-40.

[8] De Groot, W.J. 1989. Development of the Saskatchewan Fire Suppression Preparedness System. Forestry Canada, Saskatchewan District Office, Prince Albert, SK. Study NOR-36-03-4 File Report No. 2 (in press).

References

ALEXANDER, M.E., AND W.J. DE GROOT. 1988. Fire behavior in jack pine stands as related to the Canadian Forest Fire Weather Index (FWI) System. Canadian Forestry Service, Northern Forestry Centre, Edmonton, AB. Poster (with text).

ALEXANDER, M.E., W.J. DE GROOT, K.G. HIRSCH, AND R.A. LANOVILLE. 1989. Use of posters for interpreting fire behavior/danger research. Fire Management Notes 50:[in press].

ALEXANDER, M.E., AND R.S. MCALPINE. 1989. Forest fire research in western and northern Canada, 1962-1987: an annotated bibliography. For. Can. Inf. Rep. NOR-X [in press].

ANONYMOUS. 1984. Canada-Saskatchewan Forest Resource Development Agreement 1984-1989. Canadian Forestry Service, Saskatchewan District Office, Prince Albert, SK. Unnumbered publication.

ANONYMOUS. 1988. New fire danger/behavior training courses in Saskatchewan. Forest Fire News 25:27-29.

BLATCHFORD, O.N. 1972. Dissemination and application of research information in the field. British For. Comm. Res. and Develop. Pap. 88.

CALLAHAM, R.Z. 1984. Managing for applications, not just for research and development. J. of For. 82:224-227.

CANADIAN FORESTRY SERVICE. 1987. Canadian Forest Fire Danger Rating System - users' guide. Produced by the Canadian Forestry Service Fire Danger Group, Ottawa, ON. Three-ring binder. Uncumbered publication. [limited distribution].

CAYFORD, J.H., AND L.F. RILEY. 1986. Technology transfer at a Canadian research centre. In Proceedings of the 18th IUFRO World Congress, Division 6: General Subjects. International Union of Forest Research Organizations, Vienna, Austria. 216-226.

DE GROOT W.J. 1987a. Examples of Canadian Forest Fire Behavior Prediction System fuel types in Saskatchewan. Canadian Forestry Service, Saskatchewan District Office, Prince Albert, SK. (Poster with text).

DE GROOT, W.J. 1987b. An overview of the Canadian Forest Fire Danger Rating System. Can. For. Serv., Sask. Dist. Off. Technol. Transfer Note S-001.

DE GROOT, W.J. 1988a. Forest ecosystems in the mixed wood section of Saskatchewan and standard fuels for predicting fire behavior. Can. For. Serv., Sask. Dist. Off. Technol. Transfer Note S-003.

DE GROOT, W.J. 1988b. Application of fire danger rating to the wildland/urban fire problem: a case study of the Nisbet Provincial Forest, Saskatchewan. In Proceedings of the symposium and workshop on protecting people and homes from wildfire in the interior west. Compiled by W.C. Fischer and S.F. Arno. USDA Forest Service, Intermt. Res. Stn., Ogden, Utah. Gen. Tech. Rep. INT-251. 166-170.

KILL A.D., D. QUINTILIO, AND M.E. ALEXANDER. 1986. Adaptation of a national system of fire danger rating in Alberta, Canada: a case study in technology transfer. In Proceedings of the 18th IUFRO World Congress, Division 6: General Subjects. Internationa Union of Forest Research Organizations, Vienna, Austria 410-421.

LAWSON, B.D., B.J. STOCKS, M.E. ALEXANDER, AND C.E. VAN WAGNER. 1985. A system of predicting fire behavior in Canadian forests. In Proceedings of the eighth conference on fire and forest meteorology. Edited by L.R. Donoghue and R.E. Martin. Society of American Foresters, Bethesda, MD. SAF Publ. 85-04. 6-16.

MARX, H.G. 1986. Planning - the bottom line of technology transfer. In Proceedings of the 18th IUFRO World Congress, Division 6: General Subjects. International Union of Forest Research Organizations, Vienna, Austria. 197-202.

MCALPINE, R.S. 1986. Forest fire growth calculator. Can. For. Serv., North. For. Cent. For. Manage. Note 35.

MCALPINE, R.S. 1987. Two BASIC programs for fire danger and fire behavior computations. Can. For. Serv., North. For. Cent. For. Manage. Note 43.

MOELLER, G.H., AND D.T. SEAL. (Editors). 1984. Technology transfer in forestry. British For. Comm. Bull. 61.

OGILVIE, C.J. 1989. Some observations on lightning fires in Saskatchewan forests. Fire Manage. Notes 50:[in press].

STOCKS, B.J., B.D. LAWSON, M.E. ALEXANDER, C.E. VAN WAGNER, R.S. MCALPINE, T.J. LYNHAM, AND D.E. DUBE. 1989. The Canadian Forest Fire Danger Rating System: an overview. For. Chron. 65:[in press].

SUTTON, W.R.J. 1986. Management of applied research - one scientist's perspective. N. Z. For. 31(2):15-18.

VAN WAGNER, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Can. For. Serv. For. Tech. Rep. 35.

The Effect of Hourly Weather on Fire Area in the FBP System

U. FEUNEKES AND I. R. METHVEN
R/EMS Research Ltd
Fredericton, New Brunswick

Abstract

The importance of using hourly weather rather than a single daily value was tested using the Canadian Forest Fire Behaviour Prediction (FBP) System. An hourly weather data set from Saskatchewan was used to compare fire areas calculated using actual hourly data as opposed to the built-in diurnal trend in the FBP System. The latter resulted in consistent and serious underestimates of fire area, and this was traced to a major difference in the diurnal trend of the relative humidity and the Fine Fuel Moisture Code. A procedure was developed for a regional estimator of hourly weather, and when this was applied to the above analysis, it generated relatively accurate and consistent fire areas with no bias.

Résumé

L'importance d'utiliser la météo horaire au lieu d'une seule valeur journalière a été testée en utilisant la méthode canadienne de prévision du comportement du feu de forêt (PCF). Un ensemble de données météorologiques horaires de la Saskatchewan a été utilisé afin de comparer les étendues du feu calculées, utilisant les données horaires actuelles au lieu des tendances diurnes dans la méthode PCF. Des sousestimations sérieuses et consistantes des étendues du feu ont été le résultat de cette dernière, et alles-ci ont été tracées à une différence majeure dans la tendance diurne de l'humidité relative et du code de la teneur en humidité du combustible léger. Une procédure pour un estimateur régional de la météo horaire à été développée, et lorsque celle-ci fut appliquée à l'analyse ci-haut, elle généra des étendues de feu relativement précises et consistantes sans préjugés.

Introduction

At the heart of the Canadian Forest Fire Behaviour Prediction (FBP) System (Alexander et al. 1984, Lawson et al. 1985) is the fine Fuel Moisture Code (FFMC). When combined with wind to generate the Initial Spread Index (ISI), the FFMC drives fire spread and fire growth. This important role is combined with an inherent instability in that the FFMC represents a fine fuel that wets and dries rapidly to yield a distinct diurnal cycle.

Unfortunately, as Van Wagner (1977) has pointed out: "this diurnal trend was bypassed by the empirical field methods and analysis used in developing the FFMC" as part of a "trend towards simplification earlier in the development of the fire danger rating system" (Van Wagner 1987). Recognition of the importance of this diurnal variation, however, goes back to at least 1939 when H. Beall produced a table of diurnal variation in fire danger (Van Wagner 1977). This early attempt was not followed up until 1969 when Muraro et al. (1969) developed a diurnal table specifically for the FFMC which Van Wagner (1972) modified and refined, specifically by revamping the F scale relative to moisture content. This work resulted in lookup tables that can be found in Canadian Forestry Service (1973, 1974), Alexander (1982) and in the interim guide to the FBP System (Alexander et al. 1984). The limitation of these tables, as with all tables simplified for manual use, is the discontinuity between values, particularly where variation in overnight humidity is assigned to one of three classes, and the need to use a single diurnal trend. The net result can be dramatic differences in predicted fire growth.

With the almost universal availability of computers throughout contemporary fire management organizations, such simplification is no longer necessary, and all manual approaches such as lookup tables should be dispensed with. This was recognized by Van Wagner (1977) when he adapted the existing equations to hourly calculation of the FFMC. The adaptation was essentially one of trial and error in which hourly and daily trends were compared and adjusted. The net

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

result was the conclusion that hourly rate of change in moisture content was best approximated by 1/8 of the standard daily rate based on the assumption that a 24-hour cycle is equivalent to 8 hours of drying weather.

The only published tests of the hourly equations were those done by Van Wagner (1977) himself. He made two tests of the hourly equations. The first, which compared actual and computed diurnal trends in moisture content of jack pine litter samples from which rain was excluded, demonstrated reasonable agreement. However, the test involved fluctuations around the equilibrium moisture content only, and was run in the climatic area (Petawawa, Ontario) in which the moisture content equations had been developed. That is, if the test had been run in a different climatic region with different diurnal relative humidity values, the agreement might not hold to the same degree. The second test involved a comparison of the standard daily and hourly FFMC values for a series of five runs starting at saturation. While the final equilibrium FFMC values at 1600 hours were in close agreement, the rate at which the values were attained was not, suggesting that the drying rates were not synchronized and thus could lead to significant FFMC and fire growth differences while the fuel was drying, but that these differences would diminish as equilibrium values were approached. While these problems are implicit in a statement by Lawson et al. (1985) that "A comprehensive, computer-compatible scheme to handle time of day, elevation, latitude, as well as slope and aspect variables is under development", no explicit, quantitative analysis of the problem of diurnal variation with latitude has been previously presented.

The objectives of this paper were to extend the tests done by Van Wagner on the hourly FFMC by utilizing weather data from a different area of the country and by evaluating the results in terms of fire area; to determine the accuracy of the interim guide to the FBP System vis a vis the hourly approach; and to develop an alternative procedure for the calculation of hourly values in the absence of hourly weather.

Approach

The approach involved three analyses and the development of a new procedure: 1) comparison and analysis of fire growth based on the FFMC adjustment in the interim guide to the FBP System (Alexander et al. 1984), with fire growth based on actual hourly weather inputs from Saskatchewan using Van Wagner's (1977) equations; 2) analysis of the results through a comparison of the standard daily outputs of the FFMC with those calculated from actual hourly weather; 3) development of an alternate procedure for estimating hourly weather and diurnal trends; and 4) comparison of fire areas generated using the actual hourly weather with those generated by the new procedure for estimating hourly weather.

The hourly weather set used in the analyses was provided by R. Jacobs of the Saskatchewan Department of Parks, Recreation and Culture. It comprised 43 station years of hourly weather from 1987 and 1988. This data set was divided into 3040 sets, each of which consisted of 36 hours of rain-free weather from 1700 hours of the first day to 0400 hours of the third day.

The 36 hour data sets from 1987 and starting FFMC values of 85 were used to calculate fire areas for each hour from 1200 to 2400 hours of the second day of each 36 hour set. These areas were then compared to the areas produced after adjusting the FFMC by one of two methods. In the first case the 1600 FFMC value (calculated by the hourly procedure) was projected back to 1200 hours and forward to 2400 hours using the standard FBP System procedures, with two adjustments: interpolation was used between table values, and the 2100 to 2400 hours values were obtained by a straight line projection from 2100 to 0600 hours based on the lowest relative humidity class of <68% (Van Wagner 1972). In the second case the actual noon weather was used to estimated weather values for the period 1200 to 2400 hours. The estimate weather values and the 1600 hour FFMC value were then used to calculate estimated FFMC and ISI values using the hourly equations of Van Wagner (1977) for the period 1200 hours to 2400 hours.

Results

The one hour fire areas calculated using the FBP System and the hourly weather data are plotted in Figures 1a and b for 1200 and 2000 hours respectively. In all cases, the starting FFMC value for the previous day was set at 85 and the current day's value calculated using the hourly weather. Wind was based on actual hourly measurements on the assumption that the wind estimates for the FBP System approach were perfect. The 1200 and 2000 hour values from the FBP System diverged strongly from those calculated using actual hourly weather. At 1200 hours the FBP System showed a strong negative bias in fire area with some values diverging up to 1000% (Figure 1a). At 2000 hours this negative bias was even more strongly pronounced with virtually all the fire areas calculated by the FBP System being consistent underestimates (Figure 1b).

Given that both approaches have used the same wind values it is apparent that the strong underestimates of fire area generated by the FBP System must be associated with the diurnal FFMC estimates. To test this conclusion, FFMC values were calculated for a day in June and one in August using the FBP System and hourly weather measurements. The previous day's 1600 hour FFMC was set at 85, the hourly FFMC values were calculated using average hourly weather for June and August, and the trends for the current day plotted (Figure 2). It is immediately apparent that the standard diurnal trend associated with the FBP System diverges strongly from the actual diurnal trend in Saskatchewan. The 1600 hour values are the same (having been calculated from hourly data) but the forward and

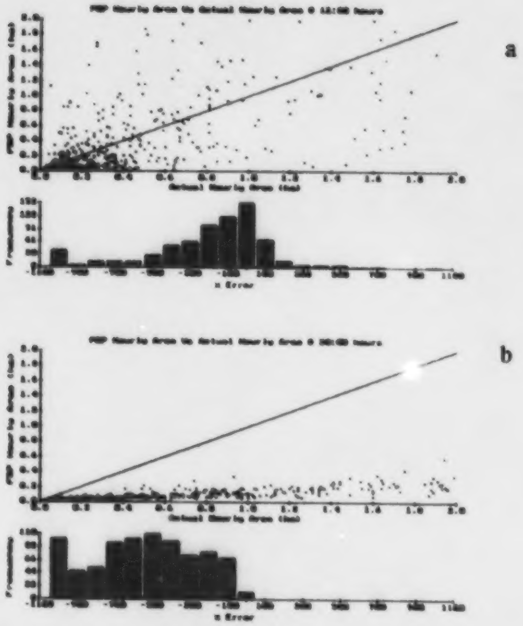


Figure 1. Hourly fire areas calculated by the FBP System plotted against areas calculated using actual hourly weather measurements: a - 1200 hours, b - 2000 hours. Bar chart displays a frequency distribution of the percent error in fire area calculated by the FBP system.

backward projections are not. The peak values for the FBP System occur at 1600 hours, while those for the hourly Saskatchewan data occur at 2000 hours and are significantly higher.

The standard diurnal trend of the FFMC contained in the FBP system did not apply to the situation in Saskatchewan in 1987, and the use of the FBP System resulted in major errors in the calculation of fire areas. This raises the question of how to obtain a better prediction of hourly weather where actual measurements are not available.

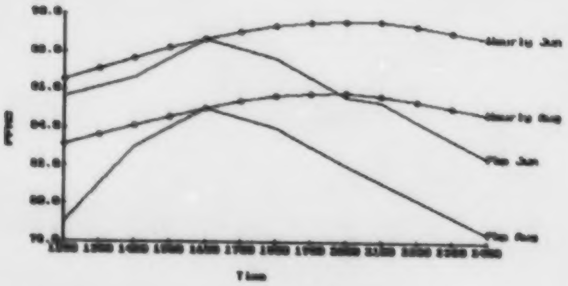


Figure 2. Diurnal trends of the FFMC in June and August calculated by the FBP System, and calculated using actual hourly weather from the 1987 Saskatchewan weather data.

The 1988 hourly weather data from Saskatchewan was used to develop a procedure for estimating hourly weather, and this procedure was used to calculate hourly fire areas. To ensure fair comparisons between the methods, actual wind measurments were used instead of the estimated wind values that the procedure produces. These areas were then plotted against the areas calculated from the actual hourly weather for 1987 at 1200 and 2000 hours (Figures 3a and b). While there is a certain amount of scatter in the data (Figure 3a) there is little bias or deviation from the actual hourly calculations. The 2000 hour results are even tighter than those from 1200, show no bias, and demonstrate the much greater accuracy of the new estimating procedure as compared to the results using the FBP System.

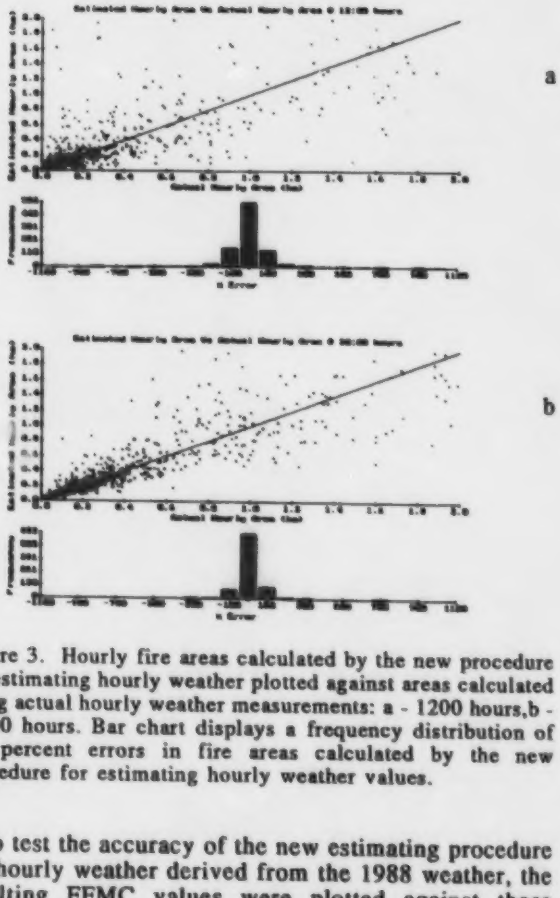


Figure 3. Hourly fire areas calculated by the new procedure for estimating hourly weather plotted against areas calculated using actual hourly weather measurements: a - 1200 hours,b - 2000 hours. Bar chart displays a frequency distribution of the percent errors in fire areas calculated by the new procedure for estimating hourly weather values.

To test the accuracy of the new estimating procedure for hourly weather derived from the 1988 weather, the resulting FFMC values were plotted against those calculated from the actual hourly weather for 1987 (Figure 4). It can be seen immediately that the correspondence is very close and much superior to that from the FBP System. This is not surprising given the nature of the diurnal pattern in the FBP System as opposed to that normally encountered in western Canada, but it does demonstrate that it is possible and highly

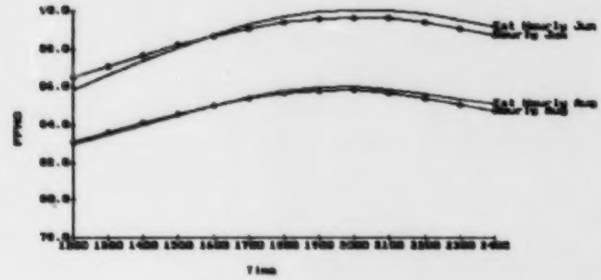


Figure 4. Diurnal trends of the FFMC in June and August calculated by the new procedure for estimating hourly weather, and calculated using actual hourly weather from the 1987 Saskatchewan weather data.

desirable to include alternative diurnal patterns within the FBP system.

Discussion and Conclusions

It is apparent that hourly weather should be used wherever possible to capture the local differences in diurnal weather patterns due to such variables as latitude, longitude and elevation. Where hourly weather is not available, diurnal trends must be devised. The standard diurnal variation contained in the interim guide to the FBP System (Alexander et al. 1984) is based on an eastern-type case where the relative humidity rises after the 1600 hour peak, and attains a value of 100% at some period during the night (Van Wagner 1989). It is planned to correct this limitation in the future (Lawson et al. 1985), but the existing pattern is not the normal pattern in much of western and northern Canada, where the humidity remains low or continues to fall after the standard 1600 hours, and rarely rises to 100% during the fire season in the absence of rain. It is apparent that the existing, though temporary, diurnal trend in the FBP System should be interpreted with care and needs to be regionalized if not localized. A procedure has been developed for estimating hourly weather in Saskatchewan that provides relatively accurate, non-biased values that may have a wider application.

Literature Cited

ALEXANDER, M. E. 1982. Diurnal adjustment table for the Fine Fuel Moisture Code. Dep. Environ., Can For. Serv., North. For. Res. Cent., For. Manage. Note No. 17. 3p.

ALEXANDER, M. E., B. D. LAWSON, B. J. STOCKS, AND C. E. VAN WAGNER. 1984. User guide to the Canadian Forest Fire Behaviour Prediction System, Interim Edition, Can. For. Serv. 76 p.

CANADIAN FORESTRY SERVICE. 1973. Adjusted Fine Fuel Moisture Code and Fire Weather Index for times throughout the day. Dep. Environ., Can. For. Serv., Pac. For. Res. Cent., Can. For. Fire Behav. Syst. Suppl. BC-6. 3p.

CANADIAN FORESTRY SERVICE. 1974. Adjusted Fine Fuel Moisture Code and Fire Weather Index for times throughout the day. Dep. environ., Can. For. Serv., Great Lakes For. Res. Cent., Can. For. Fire Behav. Syst. Suppl. ONT-#. 3p.

LAWSON, B. D., B. J. STOCKS, M. E. ALEXANDER, AND C. E. VAN WAGNER. 1985. A system for predicting fire behaviour in Canadian forests. In Proc. Eighth Conf. Fire and For. Meteorol., Soc. Am. For., Washington, D.C.

MURARO, S. J., R. N. RUSSELL, AND B. D. LAWSON. 1969. Development of diurnal adjustments table for the Fine Fuel Moisture Code. Can. For. Serv., Pac. For. Res. Cent., Inf. Rep. BC-X-35. 24p.

VAN WAGNER, C. E. 1972. A diurnal table for the Fine Fuel Moisture Code. Can. For. Serv., Petawawa For. Exp. Sta. Inf. Rep. PS-X-38. 8p.

VAN WAGNER, C. E. 1977. A method of computing fine fuel moisture content throughout the diurnal cycle. Dep. Environ., Can. For. Serv., Petawawa For. Exp. Sta. Info. Rep. PS-X-69. 15 p.

VAN WAGNER, C. E., AND T. L. PICKETT. 1985. Equations and FORTRAN program for the Canadian Forest Fire Weather Index System. Can. For. Serv. Tech. Rep. 33. 18 p.

VAN WAGNER, C. E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Can. For. Serv., For. Tech. Rep. 35. 37 p.

VAN WAGNER, C.E. 1989. Personal communication.

Le système de gestion en protection des forêts du Québec

J. GUENETTE
Centre de Transfert Technologique de Maniwaki
Maniwaki, Québec

Résumé

Le système de gestion en protection des forêts du Québec (SGPF) a pour objectifs:

- de prévoir les feux;
- de prévoir leur impact;
- et de prévoir les résultats de l'application de diverses stratégies d'intervention.

Le SGPF repose sur un ensemble de programmes informatisés, développés par l'Institut forestier national de Petawawa et testés régulièrement dans le contexte opérationnel de la Société de conservation de l'Outaouais.

Le Centre de transfort technologique de Maniwaki (CTTM) s'occups d'adapter ces programmes dans le but de les rendre fonctionnels dans les autres Societéts de conservation et au Centre provincial de coordination de la lutte situé à Québec.

Le kiosque du CTTM comprend les équipements nécessaires à la démonstration interactive des produits du SGPF.

Abstract

The objectives of the Quebec Forest Protection Management System are:

- to forecast fires;
- to forecast their impact;
- to forecast the results of applying a variety of action strategies.

The System is based on a set of computer programs developed by the Petawawa National Forestry Institute. These have been regularly tested in the operational context of the Ottawa Valley Conservation Authority. The Maniwaki Technology Transfer Centre (MTTC) is adapting the programs for use by the other conservation authorities and by the provincial fire co-ordination centre in Quebec City.

The MTTC booth can provide an interactive demonstration of the System's outputs.

GIS Applications in Fire Management

R. VAN WYNGAARDEN
Tydac Technologies Inc.
Ottawa, Ontario

T. GRIMES
Maniwaki Technology Transfer Centre
Maniwaki, Québec

Abstract

Geographic Information Systems (GIS) have received a lot of attention recently, and are becoming extremely popular amongst foresters. To date most GIS have been concentrating on the storage and retrieval of geographic data, and not as much on the analytical aspects that GIS are capable of doing.

An operations oriented GIS can provide a powerful tool in day to day fire management;

(a) in the storage of pertinent data:

- forest inventory maps
- landsat fuel classifications/enhancements
- road/access maps
- water body classifications
- value to protect maps

(b) in data analysis and modeling:

- impact of fuels/topography on daily fire danger
- fire growth simulation
- establishment of initial attack priorities
- fire line construction tactics
- optimized resource displacements
- turnaround time estimation for air drops
- post mortem fire assessments

Résumé

Depuis un certain temps, beaucoup d'interet est porte envers les Systemes d'Information a Reference Spatiale (SIRS), qui sont devenu tres populaires parmis les gens ocuvrant foresterie. La plupart de SIRS sont toutefois plus utilises pour leurs fonctions d'archivage et d'extraction de donnees geographiques que pour leurs capacites analytiques.

Un SIRS oriente vers un usage operational peut devenir un outil bres puissant pour le gestionnaire de la foret;

(a) Par l'archivage de donnes pertinentes:

- Cartes d'inventaire forestier
- Classification/Rehaussement de donnees de combustible a partir d'imagerie satellite
- Cartes de routes et de points d'access
- Cartes de classification des points d'eau
- Cartes des valeurs a protager

(b) Par l'analyze et la simulation:

- Evaluation des effets des combustibles et de la topographie sur le danger de feu en foret
- Determination des priorities lors d'altaque initiale
- Tactiques de construction de lignes d'arret
- Optimisation du deplacement des ressources
- Estimation du cycle des largages aeriens
- Evaluation historique de feux

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

A Spatial Analysis Approach for Forest Fire Preparedness Planning

B. S. LEE
K. R. ANDERSON
Forestry Canada
Edmonton, Alberta

Abstract

This paper describes how spatial analysis can be applied to forest fire preparedness planning. Using interpolation techniques, Canadian Forest Fire Weather Index (FWI) System inputs and outputs can be estimated between weather stations. When the interpolated FWI system outputs are used in conjunction with Canadian Forest Fire Behavior Prediction (FBP) System fuel types interpreted from forest inventories, the fire behavior potential can be evaluated spatially for the wildland protection area. Fire behavior potential maps such as forward rate-of-spread and crowning potential can be simulated using this approach. When potential fire size and initial attack policies are incorporated, an attack time objectives map is produced for the protection area. Resource deployment is evaluated by comparing fire control resource positioning with the attack time objectives map. The net product of this analysis is the coverage assessment map. This product classifies the forest on the basis of no coverage, coverage by one resource, or coverage by two or more resources.

Résumé

Ce document décrit comment l'analyse spaciale peut s'appliquer à la planification de la préparation de la défence contre les incendies. En utilisant des techniques d'interpolation, les intrants et extrants de l'indice Forêt-Météo Méthode Canadienne (IFM) peuvent être estimés entre les stations météorologiques. Lorsqu'on se sert conjointement des extrants interpolés provenant de la méthode IFM, avec les genres de combustibles de la méthode canadienne de la prévision du comportement des incendies, interputés à partir des inventaires de la forêt, le potentiel du compostement du feu peut être évalué en espace pour l'endroit de protection de la friche. En utilisant cette approche, des cartes du potentiel du comportement des incendies tels que le taux de vitesse avant et le potentiel de la cime peuvent être simulés. Lorsque la grandeur potentielle de l'incendie et les directives d'attaque initiale sont incorpories, une carte des objectifs de l'heure d'attaque est produite pour l'endroit de protection. Le deploiement des ressources est évalué en comparant le positionnement des ressources de contrôle de l'incendie avec la carte des objectifs de l'heure d'attaque. Le produit net de cette analyse est la carte de détermination de la couverture. Ce produit classifie la forêt sur une base d'aucune couverture, couverture par une ressource, ou couverture par deux ressources ou plus.

Introduction

Preparedness planning is the process of determining the fire control resource levels required to meet, or at least cope with, an anticipated fire situation. This planning is done by the fire manager, either during the morning or the previous evening. Using forecasted weather values to determine the relative fire danger for the next burning period, and a knowledge of wildland fuels and values-at-risk, the fire manager can make qualitative assessments of the resource levels and positioning required for the target period.

The purpose of this paper is to describe a quantitative approach that employs spatial analysis techniques for forest fire preparedness planning. The objective is to improve our presuppression deployment of fire control resources.

Preparedness Planning in Canada

A number of fire management agencies in Canada have developed preparedness planning schemes in recent years. While these systems vary in complexity and approach, they all strive to meet the same objective of ensuring rapid and adequate initial attack. The Presuppression Preparedness System (PPRS) described by Gray and Janz (1985) outlines the initial attack scheme presently used by the Alberta Forest Service. The preparedness level for each forest is determined from tables using ranges in component values derive from the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987). The preparedness, or man-up, level dictates the amount of fire suppression resources to be activated by the forest based on these predetermined fire danger ratings.

Within the forest, attack time objectives (or initial attack objectives as stated in this text) are determined using FWI system value ranges. The attack time objective defines a sphere of influence for fire suppression resources. The regional fire manager then

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

deploys these resources at bases within the forest attempting to maximize their coverage or minimize their response time.

Since 1985, the PPRS has incorporated fire growth predictions using the Canadian Forest Fire Behavior Prediction (FBP) System (Lawson et al. 1985). The attack time objective has been revised to the growth time required for a hypothetical fire to reach 1.2 ha in the worst case fuel type (black spruce) under the given FWI conditions.

Though this system has been successful in reducing the number of campaign fires in Alberta, the authors recognize that an overmanning problem may exist. This situation stems from inadequate handling of spatial data - namely fuels, weather and terrain. Often, the worst case weather and fuel within a forest or initial attack zone is used to determine deployment requirements. A more detailed approach is generally beyond the limits of an operational office.

Intelligent File Management Information System

Recent developments have made the personal computer a practical tool for fire management. Larger storage and faster processing capability make the management and integration of large databases, such as forest inventories and weather, more feasible. With easy access to this information, a fire manager can analyze and support his decisions with site specific records and spatially interpreted data.

The Intelligent Fire Management Information System (IFMIS) is a microcomputer based software package under development at Forestry Canada's Northern Forest Centre (Lee 1989). IFMIS is a decision support system for use in forest fire preparedness planning and in the initial attack dispatching of fire suppression resources. Integrating mathematical modeling, geographical information systems, and expert systems, IFMIS aids the fire manager in the decision making process by conducting a more detailed approach to preparedness planning. This approach is presented in this paper.

Canadian Forest Fire Danger Rating System

IFMIS uses the Canadian Forest Fire Danger Rating (CFFDRS) System as a model to predict fire danger and fire behavior in Canada (Stocks et al. 1989). It has been in development for over twenty years and has proved quite successful in describing the fire environment. The CFFDRS is an integral component of IFMIS for its fire behavior modeling.

The CFFDRS consists of two subsystems: the Canadian Forest Fire Weather Index (FWI) System (Van Wagner 1987) and the Canadian Forest Fire Behavior Prediction (FBP) System (Lawson et al. 1985). The FWI system estimates forest moisture conditions with the input of daily weather. These inputs are: temperature, humidity, wind, and precipitation. The FBP system predicts fire behavior using FWI system outputs, FBP fuel type classifications, and terrain characteristics. Outputs from the FBP system are the forward rate-of-spread, the fire shape, size, and perimeter.

Interpolating Fire Weather

A problem faced when handling weather information is how to interpret values between stations. The standard approach used by meteorologists is to contour the information by eye. Computer systems for national weather services use objective analysis schemes to derive a spatial field. This is done by balancing observed data with dynamics relationships in the atmosphere, such as the geostrophic wind relation (Haltiner and Williams 1980). While the FWI system uses weather data as inputs, the output values are statistically based and do not lend themselves to objective analysis. As a result, alternative interpolation techniques must be used.

INTERPOLATION TECHNIQUES

The first interpolation technique that is intuitively obvious is a nearest neighbor approach. This technique interpolates the FWI output values at a given point as equal to those of the closest weather station. Though this technique has the merit of being easy to apply and understand, it has serious drawbacks. Spatially, this technique creates a patchwork of polygons known as Theissen polygons, which have no bearing on climatology or topography. Being a choropleth technique, each polygon has constant FWI values and at the boundaries, sharp discontinuities occur as values step up or down to the values in the neighboring polygon. Figure 1a illustrates a nearest neighbors analysis of the buildup index (BUI) for May 4, 1988. Theissen polygons are outlined. The BUI value within each polygon is constant and equal to the value at the weather station within the polygon.

The current interpolation technique used by most forestry agencies is cell assignment. Cell assignment is a choropleth technique that designates a region of influence for each weather station. All points within the region are assumed to have the same weather as the station. Cell assignment is a more reasonable technique as it allows for climatological and topographical considerations. For example, weather within a mountainous region would be best represented by a weather station within the region than one outside, even though the latter may be closer to some points within the region. But, like the nearest neighbor technique, cell assignment has the disadvantage of not creating a smooth value gradient between stations. Another disadvantage is the amount of time and expert knowledge required to designate effective assignment regions. Figure 1b shows a cell assignment analysis of the BUI for May 4, 1988. The forest has been divided into regions. Each region has an assigned weather station. The BUI value of the region is constant and equal to the value at the assigned weather station.

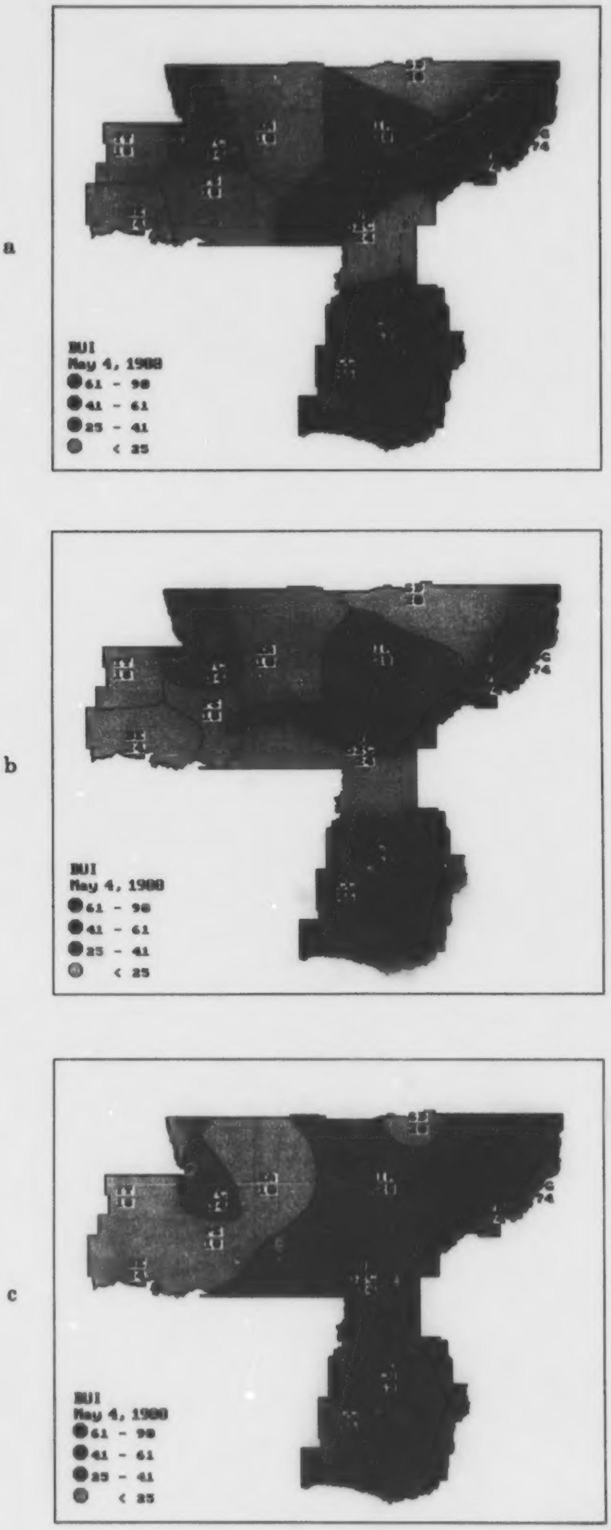

a
BUI
May 4, 1988
61 - 98
41 - 61
25 - 41
< 25
b
BUI
May 4, 1988
61 - 98
41 - 61
25 - 41
< 25
c
BUI
May 4, 1988
61 - 98
41 - 61
25 - 41
< 25

FIG. 1. Schematics of how (a) nearest neighbor, (b) cell assignment, and (c) weighted moving averages analysis techniques for the Buildup Index, as derived from the Canadian Forest Fire Weather Index (FWI) System, for May 4, 1988. The BUI values for each station are placed under their two letter identifier.

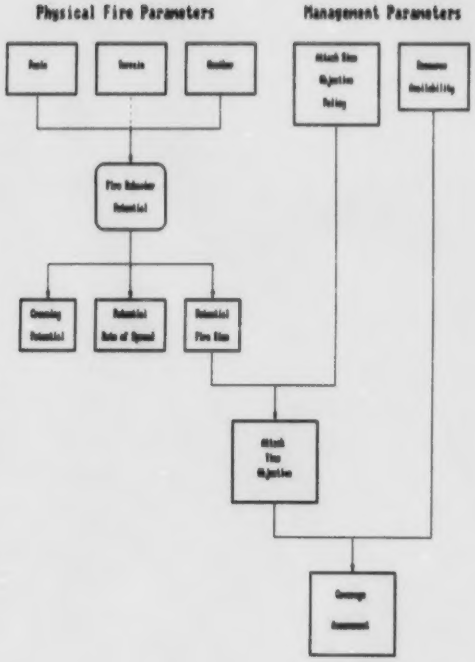


FIG. 2. Spatial modelling of the fire environment used to derive the coverage assessment.

The third interpolation technique uses a weighted moving average. This technique interpolates values between stations by considering FWI output values from all close weather stations and weighting them with a function of the distance from the station to the point of interest. The definition of a close weather station is purely subjective with the intent of reducing calculations by rejecting distant weather stations

Weighting functions vary, and for this study, station values were weighted by the inverse of the distance away from the point of interest squared. In mathematical form, the weighting scheme would be

$$x' = \frac{\sum_{i=1}^{n} x_i/d_i^2}{\sum_{i=1}^{n} 1/d_i^2}$$

here x represents the station values, d represents the distance of the station from the interpolation point, and n represents the number of weather stations used in the calculation. The interpolated value is x'.

The weighted moving averages technique's advantage is that it produces an isopleth map with smooth gradients for the FWI output values between stations. One disadvantage of this technique is that it disregards the climatological and topographical arguments used in designating assignment regions, such as winds channelled by a valley. However, gradients in environmental values caused by gradual changes in elevation are represented by this technique. Figure 1c shows a weighted moving averages analysis of the BUI for May 4, 1988. BUI values at the weather stations are shown but the values throughout the map vary gradually. The boundaries between two classification represent contours of constant value.

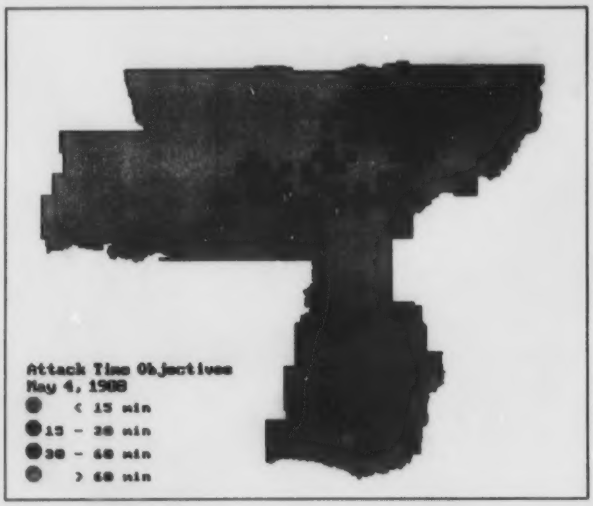


FIG. 3. Attack time objectives analysis for May 4, 1988, showing the elapsed time required for a potential fire in each cell to reach the attack size objective of 1.2 ha. Cell sizes are 2331 ha.

Spatial Modeling of the Fire Environment

Forest inventory data and interpolated weather can be integrated to predict potential fire behavior spatially. This information can be used to conduct an assessment of coverage efficiency for deployment planning. The following describes the methodology of such a technique, as used by IFMIS. The data used for this paper are from the Whitecourt Forest in the Province of Alberta, as shown schematically in Figure 2.

FOREST FUELS

Most forestry agencies have compiled forest inventories over large areas giving a detailed description of forest stands within each area. Stand descriptions include information on tree species, densities, heights and stand age. Alberta's Phase 3 Forest Inventory, completed in 1984, has evaluated the province's forest resources and stored the information in a database at a 64.75 ha cell size (0.6475 square km).

FBP fuel types can be interpreted from forest inventories to give a spatial representation of FBP fuel types. The decision criteria used to interpret FBP fuel types from the Alberta phase 3 forest inventory is outlined in Table 1.

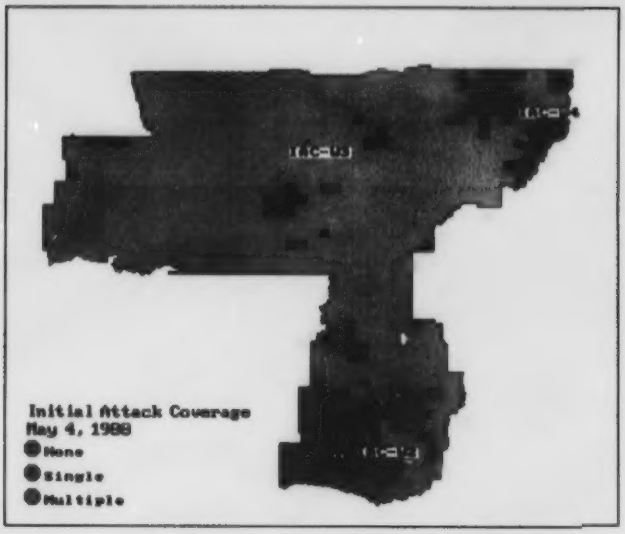


FIG. 4. Initial attack coverage assessment for May 4, 1988, using three initial attack crews: IAC-W2, IAC-W3, and IAC-W4.

TERRAIN

The FBP system allows for terrain inputs when calculating predicted fire behavior. Adjustments are made for slope and aspect when predicting to the forward rate-of-spread. Terrain was not used in this study; however, its use in the future would likely produce better estimates of fire behavior potential.

FORECASTED FIRE WEATHER

Using forecasted FWI system inputs (temperature, relative humidity, wind speed, and precipitation), the forecasted FWI system outputs are computed for each weather station in the protection area. A forecasted field is produced for the area by interpolating the values at intermediate points from the values at weather stations.

WILDLAND FIRE BEHAVIOR POTENTIAL

A spatial representation of potential fire behavior can be built by using the FBP fuel type(s) and the interpolated weather at each cell as FBP system inputs. FBP system outputs include forward rate-of-spread, crowning potential, fire shape, size, and perimeter.

ATTACK TIME OBJECTIVE

The goal of preparedness planning systems is to reach and conduct initial attack on all fires before they reach a threshold size. The threshold size is called the attack size objective. Using the FBP system outputs, the time it takes a fire to reach the attack size objective can be calculated. The time elapsed is called the attack time objective. Attack time includes report time, get-away time, and travel time of the initial attack resources.

Cell by cell fire behavior potential calculations produce a map of required attack times to meet the attack size objective. This map is referred to as the attack time objectives map. Figure 3 shows the May 4, 1988 attack time objectives analysis for the Whitecourt Forest in Alberta using the attack size objective of 1.2 ha. With this map, a forest protection officer can see areas of concern (low attack times) when rapid initial attack is required to prevent the escaped fire scenario. Note that in figures 4 and 5, a larger cell size (2331 ha or 23.31 square km) has been used to enhance clarity.

COVERAGE ASSESSMENT

The fire manager can quantitatively evaluate the deployment of fire control resources based upon the number of resources that are able to meet the attack time objective for each cell in the forest. Figure 4 shows the initial attack coverage assessment of 3 crews for May 4, 1988. The coverage value (none, single, multiple) indicates the number of resources (0).

Discussion

The deployment analysis technique as described in this paper can aid fire managers by assessing initial attack coverage effectiveness. Using this technique, the manager can deploy resources and assess the coverage. Any weaknesses in the deployment are recognized, resources are repositioned, and another coverage assessment can be produced. Using current microcomputer technology, IFMIS allows the user to consider various deployment strategies within minutes.

The proposed system does have limitations. Its accuracy depends greatly on the accuracy of the data, the interpolation technique, and the models. This is easy to overlook when faced with the final product. As IFMIS is installed in various locations in western Canada, an assessment of these problems and any others will determine the practicality of IFMIS as a fire management support tool.

Conclusions

Current presuppression preparedness systems integrate fire weather values spatially into their decision making, although at a cartographically generalized scale. With the development of computer based systems such as IFMIS, interpolated weather and forest inventory data can be used to derive cartographically detailed interpretations of predicted fire behavior. The result will be more effective positioning of initial attack resources. In addition, there is a potential for large savings of presuppression dollars by ensuring that resources are pre-positioned optimally, and only when they are needed.

Table 1. **Alberta Phase 3 Inventory to Canadian Forest Fire Behavior Prediction (FBP) System fuel type interpretation.**

Species	Density (% crown closure)		Age (years)	FBP fuel type
Treed marsh Open muskeg				C1 Spruce - lichen woodland
Black spruce White spruce Balsam fir Tamarack larch	≤ 30%			C1 Spruce - lichen woodland
Black spruce White spruce Balsam fir Tamarack larch	> 30%			C2 Boreal spruce
Coniferous scrub				C2 Boreal spruce
Pine	≤ 70%	or	≥ 30	C3 Mature jack pine or lodgepole pine
Pine	> 70%	and	< 30	C4 Immature jack pine or lodgepole pine
Douglas fir				C7 Ponderosa pine or douglas fir
Aspen White birch Balsam poplar Deciduous scrub				D1 Leafless aspen (dependent on season)
Brush Clearing Cultivated Grass				O1 Grass
Clearcut Scarified			≥ 3	O1 Grass
Clearcut Scarified			< 3	S1 Jack pine lodgepole pine slash
Insect killed Various killed Windfall				S1 Jack pine lodgepole pine slash
Recent burn Barren soil Glacier Barren rock Sand Water				NF Non-fuel

References

ALBERTA ENERGY AND NATURAL RESOURCES. 1985. Alberta Phase 3 Forest Inventory: Forest Cover Type Specifications. Edmonton, Alberta. ENR Report No. Dept. 58.

BURROUGH, P.A. 1986. Principles of geographic information systems for land resources assessment. Clarendon press, Oxford, England. 194 p.

GRAY, H.W., AND B. JANZ. 1985. Initial-attack initiatives in Alberta: a response to the 1980s. In Proc. of the Intermountain Fire Council 1983 Fire Management Workshop. Banff, Alta. 25-27 Oct, 1983. Can. For. Serv., North. For. Cent., Edmonton, Alta. pp. 25-35. Info. Rep. NOR-X-271.

HALTINER, G.J., AND R.T. WILLIAMS. 1980. Numerical Prediction and Dynamic Meteorology. John Wiley & Sons, Inc., Toronto.

LAWSON, B.D., B.J. STOCKS, M.E. ALEXANDER, AND C.E. VAN WAGNER. 1985. A system for predicting fire behavior in Canadian forests. Pages 6-16 In L.R. Donoghue and R.E. Martin, editors, Proceedings of the eighth conference on fire and forestry meteorology. Soc. Am. For., Bethesda, Maryland. SAF Publ. 85-04.

LEE, B.S. 1989. Use of advanced concepts in dispatching fire control resources. In First Interior West Fire Council Annual Meeting and Workshop. Kananaskis Country, Alta. 24-27 Oct., 1988. Forestry Canada, North. For. Cent., Edmonton, Alberta. (in press)

STOCKS, B.J., B.D. LAWSON, M.E. ALEXANDER, C.E. VAN WAGNER, R.S. MCALPINE, T.J. LYNHAM, AND D.E. DUBE. 1989. The Canadian Forest Fire Danger Rating System: an overview. For. Chron. 65: 258-265.

VAN WAGNER, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Can. For. Serv., Ottawa, Ontario. For Tech. Rep. 35.

Fire Detection Using the NOAA-N Satellites

G. STEPHENS
M. MATSON
NOAA/National Environmental Satellite, Data, and Information Service
Washington, D.C.

Abstract

Due to increased concern over the climatic and economic impacts of fires associated with deforestation and seasonal burning, most of which occurs in remote parts of the world, it is necessary to find ways to effectively monitor such activity. The 3.8 micrometer channel onboard the National Oceanic and Atmospheric Administration's polar-orbiting satellites is very sensitive to high temperature sources such as fires. Case studies in Brazil, North America, and the Soviet Union have been selected to demonstrate the utility of this channel for fire detection.

Résumé

En raison de la préoccupation grandissante à l'égard des incidences climatiques et économiques des incendies associées au déboisement et au brûlage saisonnier, phénomènes qui s'observent surtout dans des régions éloignées du globe, il est nécessaire de trouver des moyens de surveiller concrètement ces activités. La voie de 3,8 micromètres embarquée à bord des satellites sur orbite polaire de la National Oceanic and Atmospheric Administration est très sensible aux sources de chaleur élevée comme les incendies. Des études de cas effectuées au Brésil, en Amérique du Nord et en Union Soviétique ont été retenues pour démontrer l'utilité de cette voie pour la détection des incendies.

Introduction

Knowledge of regional and global fire activity is important for atmospheric, climatic, and deforestation studies. Biomass burning is a major source of gases and particulates that may contribute to the "greenhouse effect". Also, this material may affect stratospheric light scattering and absorption, acidify rainfall, and affect radiative balances and evapotranspiration.

Current fire detection methodologies are inadequate for monitoring fire activity in remote areas of the world such as the tropics, northwestern Canada, and Siberia. Ground-based detection systems usually suffer from limited aerial coverage. The value of airborne bispectral thermal infrared sensors for improved spatial and temporal coverage of fire activity has been demonstrated (Binenko et al. 1974, Warren 1984). These studies found the 3-5 micrometer portion of the light spectrum is particularly sensitive to high temperature targets such as fires. Aircraft surveys over large areas, however, are not an economical means of detecting fires. Several planes and many days of flying time are required to monitor active fire sites. Environmental satellites, such as the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites, with large view angles, daily day and night coverage, and sensors in the 3-5 micrometer spectral band, offer a potential solution to the problem of efficiently and economically detecting and monitoring fires in remote areas.

The NOAA-N Satellites

NOAA's National Environmental Satellite, Data, and Information Service operates a system of polar-orbiting satellites in sun synchronous orbits, designated the NOAA-N series. Currently, there are two satellites in operation, NOAA-10 and NOAA-11, at an altitude of 850 km. Local equatorial crossing times are 0730 h and 1930 h for NOAA-10, and 1400 h and 0200 h for NOAA-11. Each satellite orbits the Earth 14 times each day, yielding two complete global views each day.

One of the primary sensors onboard the NOAA-N satellites is the Advanced Very High Resolution Radiometer (AVHRR). This scanning instrument acquires data in five spectral channels: one in the visible range (channel 1: 0.55-0.68 micrometers), one in the near infrared range (channel 2: 0.725-1.1 micrometers), and three in the thermal range (channel 3: 3.53-3.93, channel 4: 10.3-11.3, and channel 5: 11.5-12.5 micrometers). Data are sensed by all 5 channels simultaneously. Data acquired by the instrument are degraded on board the satellite to 4 km resolution and recorded for later transmission to one of two NOAA receiving stations, at Gilmore Creek, Alaska and Wallops Island, Virginia. This is known as

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

the Global Area Coverage (GAC) mode of transmission. In addition, the full resolution 1.1 km data can be recorded for previously scheduled areas of the world, in the local Area Coverage (LAC) mode, or can be received directly from the satellite by properly equipped receiving stations, in the High Resolution Picture Transmission (HRPT) mode.

Fire Detection Methodology

Matson and Dozier (1981), Matson et al. (1984, 1987), and Muirhead and Cracknell (1984, 1985) have demonstrated that the use of the 3.8 micrometer thermal infrared channel onboard the NOAA polar-orbiting satellites provides the capability to detect high temperature sources such as steel plants, waste gas flares and fires. Figure 1 shows why this is so. For high temperature targets, the maximum blackbody radiance shifts away from the 11 micrometer channel and toward the 3.8 micrometer channel. Figure 2 shows a typical satellite-derived temperature plot over two high temperature sources located in Idaho. Target 1 is a small controlled forest burn and target 2 is a phosphorous plant operated by the FMC Corporation in Pocatello, Idaho. At these sources, the 3.8 micrometer temperatures are 16.2°K and 33.9°K higher than the corresponding 11 micrometer temperatures. Typical temperature differences between the two channels over land surfaces are usually 1-2°K. Using an algorithm developed by Matson and Dozier (1981), it is possible to utilize the temperature difference in the two channels to estimate the area and temperature of the high temperature source causing the 3.8 micrometer response. For the two sources in Figure 2, the area and temperature were 0.28 hectares and 430°K for target 1, and 1.7 hectares and 483°K for target 2. As evidenced by the calculated target sizes and the detection of the phosphorous plant, it does not take a 1.1 km target to cause a response in the 3.8 micrometer channel. Thus, small subresolution scale high temperature sources, such as fires, can be detected by the 3.8 micrometer channel.

Case Studies

Tucker el al. (1984) used NOAA-7 data taken on July 9, 1982 to identify a large (100 km by 400 km) area in Rondonia, Brazil where massive deforestation is occurring. Figures 3 and 4 are 3.8 micrometer images of this area taken on July 26, 1984 and August 18, 1988. The images show a series of warmer (gray) linear features radiating from highway BR-364 (gray, diagonal linear feature). These features were seen on the July 9, 1982 imagery and were interpreted to be large-scale, systematic forest disturbances. A field verification mission in 1982 found that the linear features were forest-clearing swaths, some at least 80 km long, about 4 km apart, and 600 to 800 m wide. The forest-clearing is part of a government-planned colonization project in which migrants are sold 100 hectare lots of forest to use for agriculture or pasture.

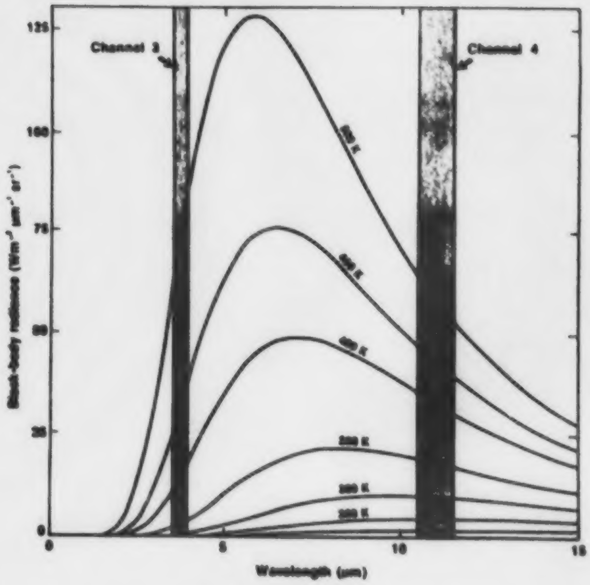


FIG 1. Planck radiances for temperatures from 200°K to 500°K. A given increase in temperature in the channel 3 segment of the curves produces a greater increase in emitted radiation than in the channel 4 segment.

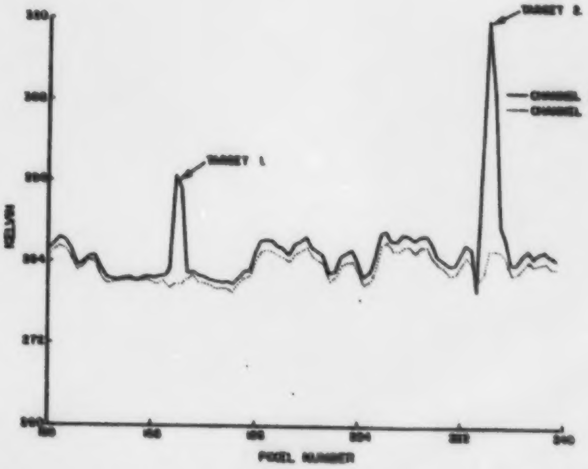


FIG 2. Channel 3 and channel 4 brightness temperature plot of hot targets 1 and 2.

Figures 3 and 4 also show many "hot spots" (white) that were not apparent on the July 9, 1982 imagery. We attribute these "hot spots" to fires caused by slash-and-burn agriculture and continued tropical forest clearing for further colonization. On the coincident visible band AVHRR imagery, the entire area was covered by smoke; further evidence that fires were occurring in the area. The fires were not detected on

FIG 3. Channel 3 AVHRR image of Rondonia, Brazil on July 26, 1984.

FIG 4. Channel 3 AVHRR image of Rondonia, Brazil on August 18, 1988.

the July 9, 1982 imagery because seasonal burning does not begin in this area until late July and August, when precipitation is at a minimum (Rudloff 1981). It can be seen that the area of forest disturbance is much greater in the 1988 scene than in 1984. By using the 1.1 km resolution AVHRR data, it would be possible to operationally monitor the expansion of deforestation and the associated burning that is occurring in this area.

Figure 5 is a channel 1 and 3 composite image over the Appalachian Mountains in the Southeastern U.S. on November 8, 1987. Again, smoke appears clearly in the channel 1 data, while fires appear as "hot spots" in the channel 3 data. U.S. Forest Service personnel attributed most of these fires, in hardwood forested areas, to human carelessness or arson, following two seasons of extreme drought. The smoke from these fires, carried by southwest winds, was later seen in New York City and New England. Note that many fires are visible in the channel 3 data even under clouds and smoke. Transmission of radiation in the 3.8 micrometer region is not significantly attenuated by water vapor, a major constituent of smoke, and thus channel 3 can "see through" smoke and thin clouds.

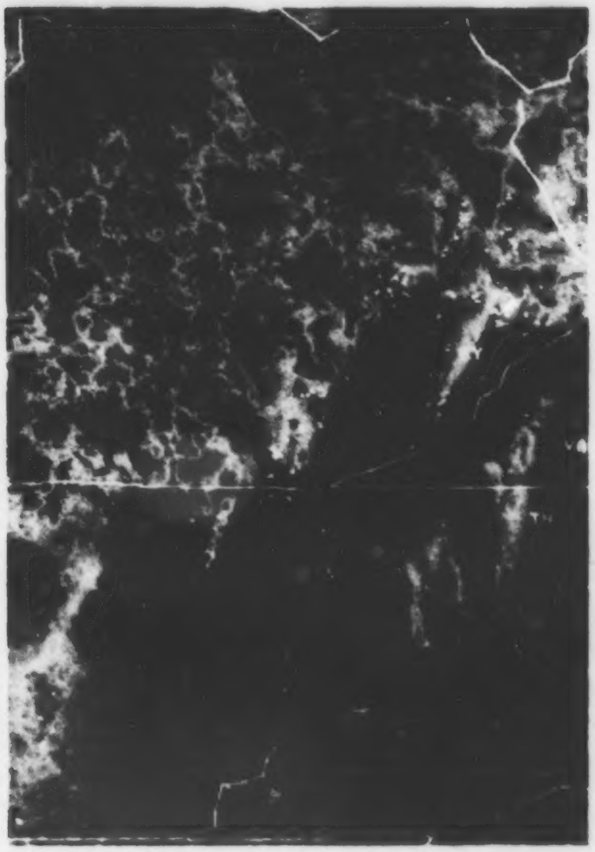


FIG 5. Combined channel 1 and 3 image of Southeastern U.S. Appalachians on November 8, 1987.

Figure 6 is a channel 1 and 3 composite image of the Yellowstone National Park area of Wyoming and surrounding states on September 7, 1988, during the height of the fires which devastated the park. The areas of active burning, again clearly visible even under heavy smoke, correlate well with later maps delineating burned areas.

The previous case studies of fire detection have utilized the 1.1 km resolution data. As described earlier, the high resolution data are only available if previously scheduled for later transmission to a satellite receiving station or if the data are obtained in an area covered by such a station. To obtain operational global coverage, the data must be in the 4 km resolution GAC mode. It might seem that such coarse resolution would be inadequate for fire detection, but as Figures 7 and 8 show, such is not the case. Figure 7 is a NOAA-7 visible band GAC image of northern Siberia, U.S.S.R., near Yakutsk, taken on July 24, 1984. The smoke plumes between 65°N to 70°N and 105°E to 125°E are a result of lightning-induced fires in this boreal forest area. Such fires are normal for this time of year and the resulting smoke has been routinely detected on NOAA satellite visible band imagery. Figure 8 is the coincident 3.8 micrometer image of the same area.

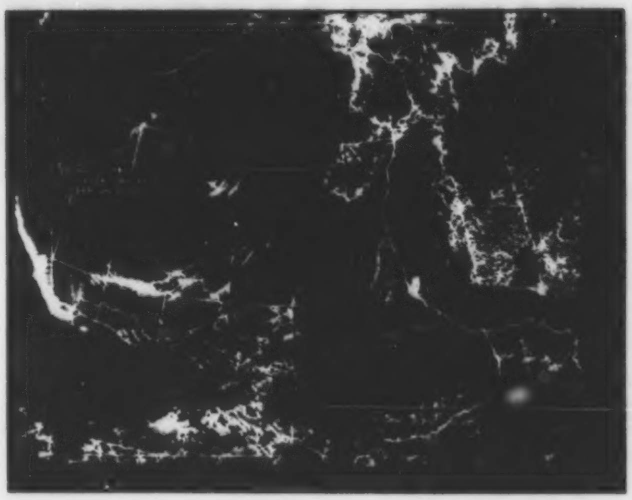


FIG 7. Channel 1 AVHRR GAC image of Siberia on July 24, 1984.

The many "hot spots" (white) on the image are the fires associated with the plume activity in Figure 7. Even at the reduced GAC resolution, the 3.8 micrometer channel responds to fire activity within the 4 km pixel. Malingreau et al. (1985) have also shown this detection capability for the 1983 fires that damaged large portions of the rain forest in Kalimantan, Borneo. More case studies of fire detection using the GAC data need to be analyzed to determine what size and temperature fires are detectable using the GAC data. Such studies may demonstrate the feasibility of global fire monitoring using the GAC 3.8 micrometer data.

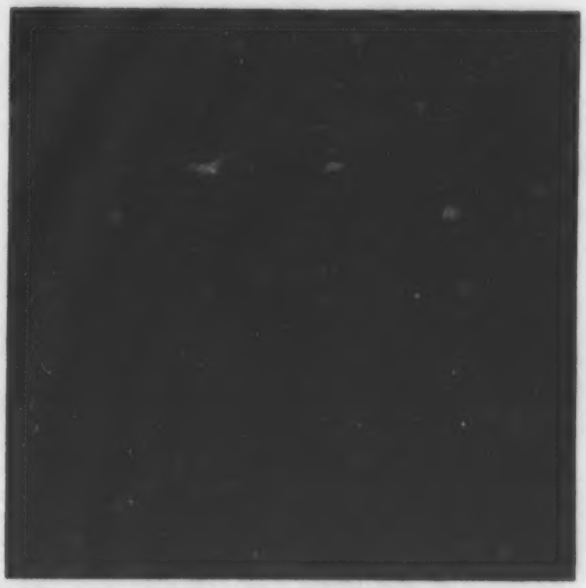


FIG 6. Combined channel 1 and 3 image of Yellowstone National Park area on September 7, 1988.

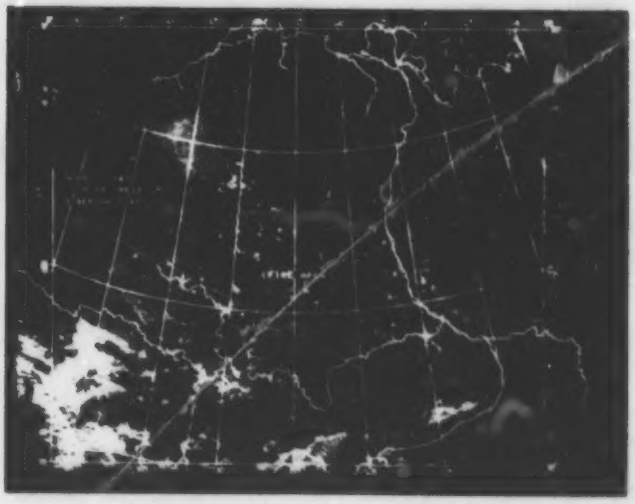


FIG 8. Channel 3 AVHRR GAC image of Siberia on July 24, 1984.

Since GAC data are routinely available with daily global coverage, NESDIS scientists conceived the idea of a continuous global fire monitoring product, using composited GAC data. Using software developed for the Operational Global Vegetation Index product, night GAC data are remapped to polar stereographic projection. The channel 3 and 4 temperatures of each pixel are then passed through an algorithm which classifies pixels as hot spots if both channels are above a certain temperature and the difference between the temperatures exceeds a set threshold. All "hot" pixels are retained, mapped to polar stereographic projection, composited over a seven day period, resampled to lower resolution, and set to a constant positive brightness for display. The final product is a polar stereographic image (Northern and Southern Hemispheres), which shows the geographic location of any spot (to within 24 km) on the Earth's surface where a high temperature source, meeting the temperature criteria above, was located at any time (during a satellite overpass) during the compositing period. A data base covering about one year has been recorded in digital format on computer compatible tapes, but has not been critically evaluated.

Figure 9 is an example of a portion of the product. Problems to be resolved include errors in the original data, which are sometimes mis-classified as hot pixels, and the identification and masking of constant heat sources. If these can be overcome, it may be possible to monitor fire activity continuously on a world-wide basis.

FIG 9. Portion of the National Environmental Satellite, Data, and Information Service's experimental global fire detection product.

Conclusions

In the past, operational fire detection over remote areas has been difficult, if not impossible. Many of these areas, such as the tropics, Siberia, and northwest Canada are major areas of seasonal burning. The difficulty in detecting and monitoring this burning has probably led to a serious underestimation of regional and global fire activity, affecting deforestation, carbon dioxide cycle, and atmospheric studies. The use of the 3.8 micrometer data from the NOAA polar-orbiting satellites offers a method of regional, and perhaps global, fire detection. This fire detection methodology could be used in conjunction with satellite-based vegetation indices (Tucker et al. 1985) to determine if changes in the indices are due to regional burning. In addition to fire detection related to climate studies, the 3.8 micrometer data can be a useful supplement to conventional fire detection techniques used in controlling fires (e.g., brush and timber fires in the western United States). The few case studies presented in this report are a sampling of what can be done to detect and monitor fires in the world. The satellite technology and data are available to be used by scientists interested in fire activity on any part of the Earth.

References

BINENKO, V.I., L.M. D'YACHENKO, K.Y. KONDRAT'EV, and A.P. CHERNENKO. 1974. In Atmospheric Radiation Studies, K.Y. Kondrat'ev, Ed. Keter Publishing House, Jerusalem.

BREEDLOVE, D. 1981. Flora of Chiapas. California Academy of Sciences, San Francisco, Ca.

GRIFFITHS, J.F. 1972. In Climates of Africa, J.F. Griffiths, Ed. Elsevier, Amsterdam.

MALINGREAU, J.P., G. STEPHENS, and L. FELLOWS. 1985. Remote sensing of forest fires: Kalimantan and North Borneo in 1982-83. Ambio. 6:314.

MATSON, M. and J. DOZIER. 1981. Identification of subresolution high temperature sources using a thermal IR sensor. Photogramm. Eng. Remote Sensing. 47:1311.

MATSON, M., S.R. SCHNEIDER, B. ALDRIDGE and B. SATCHWELL. 1984. Fire Detection Using the NOAA-Series Satellites. Department of Commerce, Washington, D.C.

MATSON, M., G. STEPHENS and J. ROBINSON. 1987. Fire detection using data from the NOAA-N satellites. Int. J. Remote Sensing. 8:961.

MUIRHEAD, K. and A.P. CRACKNELL. 1984. Identification of gas flares in the North Sea using satellite data. Int. J. Remote Sensing. 5:199.

MUIRHEAD, K. and A.P. CRACKNELL. 1985. Straw burning over Great Britain detected by AVHRR. Int. J. Remote Sensing. 6:827.

RUDLOFF, W. 1981. World-Climates. Wissenschaftliche Verlagsgesellschaft, Stuttgart.

TUCKER, C.J., B.N. HOLBEN and T.E. GOFF. 1984. Intensive forest clearing in Rondonia, Brazil, as detected by satellite remote sensing. Remote Sensing Environ. 15:255.

TUCKER, C.J., J.R.G. TOWNSHEND and T.E. GOFF. 1985. African land cover classification using satellite data. Science. 227:369.

WARREN, J.R. 1984. Thermal Infrared Users Manual. Department of Agriculture, Washington, D.C.

Monitoring the 1987 Extreme Fire in Daxinganling and Post-Fire Survey Using Space Remote Sensing Images

YANG YUN-QIAN
Heilongjiang Forest Protection Research Institute
Harbin, People's Republic of China

LI QUAN-BIN
Daxinganling Forest Fire Management Centre
Jiagedaqi, People's Republic of China

Abstract

This report describes the Daxinganling forest region in northeastern China and a large forest fire that burned from May 6 - June 2 in 1987. The burned area of the fire reached 1.33 million ha.

The report describes the use of NOAA/AVHRR and Landsat TM images to monitor the life span of the fire: fire ignition, blow-up, spread and extinguishment. The interpretations of the images were made for fire behavior analysis, post-fire survey of the tree damage classes, and calculation of burned area.

The remote sensing technology has proved to be a time-efficient and economic means of monitoring extreme fire conditions and post-fire survey. During the extreme fire the national fire center, provincial fire center and regional fire center had timely use of this satellite information for planning fire suppression.

The report presents high-quality images produced by China Satellite Meteorological Centre and China Remote Sensing Satellite Ground Station.

Résumé

Ce rapport décrit la région forestière Daxinganling au nord-est de la Chine òu un large feu de forêt qui a brûlé du 6 mai au 2 juin en 1987. La superficie brûlée par le feu a atteint 1,33 million ha.

Le rapport décrit des images NOAA/AVHRR et Landsat TM qui servaient à le surveillance de la vie du feu: l'allumage du feu, l'éclatement, propagation et l'extinction. L'interprétation des images a été faite pour l'analyse du comportement de l'incendie, l'inspection post-incendie des classes de dormmage des arbres et la calcul de la superficie brûlée.

La technologie de télédétection s'est prouvée un moyen économique qui permet de riduire le temps de surveillance de conditions extrêmes d'incendies et d'inspection post-incendie. Les centres national, provincial et régional d'incendie avaient a leur portée de l'information opportun via cet satellite pour la planification de la suppression du feu durant la période extrème de l'incendie.

Le rapport présente des images de bonne qualité produites par le China Satellite Meteorological Centre et le China Remote Sensing Satellite Ground Station.

Introduction

The applications of remote sensing technology for classifying forest fuel types, monitoring fire behavior and surveying post-fire conditions have been studied by the Heilongjiang Forest Protection Institute since the early 1980s (Yang 1981, 1982, 1983, 1985). In 1985, satellite monitoring of forest fires was successfully put into experimental operation in the Satellite Meteorological Center of the State Meteorological Administration. In 1986 the China Remote Sensing Satellite Ground Station was set up in Beijing. Since then, Chinese forest fire management has entered the "space age".

The 1987 Daxinganling fire, the largest fire on record in China, pushed the experiment into routine operation. During the fire period, the NOAA satellites passed over the fire area 109 times from May 6 to June 2. A total of 343 images were received, processed and sent to command headquarters, which helped fire bosses to analyze the fire situation and to make suppression plans. Meanwhile Landsat images of 13, 20, 23, 30 May and 6 June were registered to the NOAA imagery for exact fire positions and post-fire survey. The remote sensing has played an effective role in monitoring fire, making decisions for fire suppression and surveying post-fire conditions.

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

Description of Forest Fire Situation in Daxinganling

The Daxinganling forest region is located in the extreme north-eastern portion of China, approaching 53°28'44" N. It falls primarily within the Heilongjiang province with an area of 84,524 km^2. The main feature within the region is the Great Xingan mountain range, with low elevations in the northern portion and rolling hills in the south. Temperatures range from -35°C to 25°C and annual mean temperature is -2°C to -6°C. Annual precipitation varies from 400 mm to 500 mm, mainly concentrated in July and August. The long season of snow cover and the deep permafrost layer reflect the cold climate in this region.

The vegetation in the forest fire area belongs to the cool climatic deciduous and coniferous forests. The vegetative types are Dahurian larch forest, Mongolian Scotch pine forest, Birch forest and Tundra-bog vegetation. The forest covers approximately 75.8% of the total area. Fires occur during the dry periods from March 15 to June 30 and from September 15 to November 15. Strong winds and low humidity make a serious fire situation. From the years 1949 to 1980, about 8,280 fires have occurred. An area of 11 million ha has burned, equivalent to 35% of total forest burned in China and equivalent to 42.5% of forest land in the Daxinganling. The average forest area burned by a fire was 1,300 ha. In the years 1972 and 1977, there were extreme forest fires which destroyed over 650,000 ha of forest in this region.

Preconditions of the 1987 Fire

1. EXTREME FIRE WEATHER DOMINATED THE FIRE AREA

The annual precipitation records of six weather stations were extremely low in 1986, only 57% - 75% of a normal year. The monthly precipitation of April 1987 was 34% for the same period during normal years. The average accumulated anomaly of relative humidity, in the period of Sept.-Dec. 1986 and of March-April of 1987, was down to -70% due to persistent drought. In general, temperatures steadily exceeded 0°C in late April, but the deciduous trees were still not greened-up in early May. On May 6 the ground temperature reached 40.6°C and the relative humidity was only 4% in the fire area. That provided a favorable condition for fire ignition. For two days after the ignition of the fire, the wind was extremely strong, maximum wind speed 50-60 km/h, and frequently shifted direction in the fire area.

2. FUEL ACCUMULATIONS

The northern portion of the region is thickly covered by well developed virgin forests interspersed by grass swamps.

There had been no large forest fires in the recent past. Thus, accumulated cured grasses, dead and drying trees, logging slash and litter formed a great fuel bed for the fire. According to an investigation (Jin K.C. 1984) in six forest districts, the fuel loads were 57.0 t/ha on southern slopes, 61.3 t/ha on hill tops, 55.6 t/ha on northern slopes.

Satellite Monitoring of Fire Spread

1. IMPORTANCE OF SATELLITE MONITORING

The great Daxinganling fire spread extremely quickly to cover a vast area with many active fire fronts. Strong winds shifted direction of spread frequently, sending smoke over the entire region, and reducing visibility to near zero. The fire bosses had a great lack of information, as normal sources such as lookout towers and detection aircraft had become ineffective.

However, satellite observation can overcome these weaknesses. The NOAA meteorological satellite series has two polar-orbiting satellite in operation. These provide wide area coverage and frequent return passes, providing four real-time images per day. Furthermore, with the wide overlap, a given area on the ground can be observed on images obtained only 3-4 hours apart.

The NOAA satellites use an Advanced Very High Resolution Radiometer (AVHRR) with five spectral Bands: ch.1 0.58-0.68µm, ch.2 0.725-1.1µm, ch.3 3.55-3.93µm, ch.4 10.3-11.3.25µm, ch.5 11.5-12.5µm.

Channel 3, short-wave thermal infrared, is sensitive to a temperature range of 543°C to 464°C, covering a general range of forest fire temperatures. It was used together with channel 1 (visible green) and channel 2 (near infrared) to make a true-colour composite in which vegetation appears as green, smoke and clouds as white, active fire bright red and burned areas dark red.

The far infrared band (ch.5) has a thermal resolution of 0.25°C and can discriminate many temperature levels, including cloud, smoke and burning areas. It can sometime delineate the fire perimeter even under cloud cover. However, with a pixel size of 1.1 km, the AVHRR does not provide truly accurate fire locations. By registering the NOAA image with the Landsat TM image, with a spatial resolution of 30 m, much more accurate locations could be obtained, particularly if both images were obtained on the same day.

2. MONITORING FIRE SPREAD

The satellite system had been monitoring the entire progress of the fire. The first period of the fire was on May 6 and May 7. On May 6, six human-caused forest fires occurred within Mohe and Tahe. Some of the fires could be identified on the NOAA image

(Figure 1). After initial attack four fires, with a total area of 30,000 ha, still remained burning on the morning of May 7. In the evening of May 7, a strong cold front from the west entered the area with a maximum wind speed of 61 km/h (Amur at 2326 hours) that drove fire spread to 10 km/h; the maximum spot fire rate of spread approached 50 km/h. Fires were blown-up, sweeping dried forests and wildly spreading. Flames went to 70 m in height and the fire temperature approached 1,000°C. The fire created convective columns and fire whirls. Within 5 hours, 4 local towns, 10 forest farms and considerable sized log stacks were reduced to ashes, leaving 50,000 homeless. The fire area covered nearly 480,000 ha by the afternoon of 8 May (Figure 2). From May 9 to May 13, the fire was a moderately spreading surface fire and the fire area was extended to 580,000 ha. By May 23, the fire grew to 1,120,000 ha in size. On May 26, the fire was under control due to 10 mm of rainfall in two days. The fire was completely put out on June 2. The final fire area was 1,330,000 ha (Figure 3).

3. SATELLITE IMAGES AIDED MAKING SUPPRESSION PLANS

To gain more detail of the fire situation, Landsat images were enlarged to scales of 1:200,000 and 1:50,000. The fire perimeter, fire-breaks and even street patterns in small towns could be seen clearly. Figure 4 shows a portion of the eastern part of the fire, with various active fire fronts, and areas where the fire had been held by wide fire-breaks.

Some imagery shows various temperature levels in the fire area, produced by density slicing the thermal infrared band of the Landsat Thematic Mapper data. The whitest areas on the image exceed a temperature of 1,000°C (Dai Chang-da 1988). Imagery showed the western part to the fire, with a mosaic of active fire, burned areas and fire-breaks. The fire command headquarters used this important information in making suppression plans.

Post-Fire Survey Using Remote Sensing Technology

Post-fire survey is important work regarding natural resources conservation. After fire, forest management agencies are concerned about area burned, degrees of forest damage, and fire losses. Post-fire surveys may include: ground surveys, aerial remote sensing, remote sensing, and multilayer surveys. Methods selected depend on the size of a fire, precision desired, survey purposes, and the budget. Here we will focus on a remote sensing survey in comparison with aerial survey.

Figure 3 (black-and-white image) shows the over all scene of the 1987 Daxinganling fire. The original picture Figure 3 is a color-composite image using Landsat-5 TM 7, TM 4, TM 3 respectively assigned to red, green, blue. In order to remove clouds on the images, three images were overlaid from May 25, May 23, June 6 in 1987. The picture looks like natural color. We could interpret from the picture shades of brown as burned area, green as unburned forests, white as roads, dark blue as rivers and creeks, light blue as smoke. The communities, lakes and railroads are also obvious features on the image.

1. ESTIMATION OF THE FIRE AREA

According to aerial survey reports from the Ministry of Forestry, the fire covered an area of 1.33 million ha of land, including 1.14 million ha of forest (870,000 ha of forest were destroyed). A total of over 80.25 million m^3 of timber stock were blackened in the fire and about 30 million m^3 of timber were killed from burning (Experts Group of China State Council 1988).

Comparing with the above, the estimate from the space survey indicated that the total fire area was 1.26 million ha in size, derived from Landsat TM imagery which was geometrically corrected, and 1.14 million ha in size derived from NOAA image (Chen Weiying 1988). The errors between aerial survey and the latter two approaches were 6% and 17%. The cost ratio of the aerial survey to the space survey was 10:1 (Yang Yun-qian 1981).

2. ESTIMATION OF DAMAGE CLASSES

Some sample plots were set up in burned forest and thinly stocked land. From the sample plot ground survey in the summer of 1987, the total burned forest was classified into four classes: severe damage, medium damage, light damage and no damage (table 1). The delineation and calculation of damaged forest area for each class was based on the images provided by space survey and aerial survey. Consequently, the error of total damaged forest area estimated by the two approaches was 3%, while errors of areas of various damage class were from 4% to 8% as well. In comparison with the aerial survey, the space survey has advantages of time-efficiency, lower cost and acceptable errors. The space survey indicates that the forest cover dropped down to 61.5% from 75.8% in Daxinganling region as a result of the fire.

Table 1. Tree Damage Classification of the Forest Fire by Two Survey Approaches

Damage	Damage Degree (%)	Aerial Survey Area (*)	Aerial Survey percentage (%)	Space Survey Area (*)	Space Survey percetange (%)
Severe	70-100	0.35	30.7	0.330	30
Median	30-70	0.21	18.4	0.198	18
Light	0-30	0.31	27.2	0.297	27
None	0	0.27	23.7	0.275	25
Total	--	1.14	100.0	1.100	100

(*) Million ha

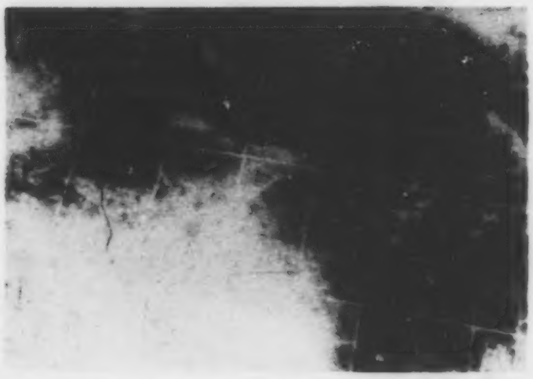


FIG 1. The fires were just detected by NOAA-9 on May 6, 15:50.

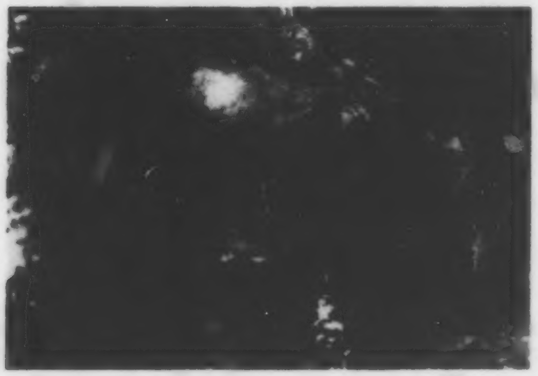


FIG 2. The fires had been extensively spread on May 8, 12:30.

Summary

The application of the satellite remote sensing technology in forest fire management has met with preliminary success in China. It showed its competitive advantages over other conventional approaches in monitoring fire situations during the extreme forest fire in 1987 under those unusual conditions.

References

CHEN WEIYING 1988. Monitoring the extent of severe forest fires in the Great Xingan Mountains using NOAA/AVHRR data. Meteorological Monthly, Vol. 14, No. 7, July, 1988, pp. 39-41.

DAI CHANG-DA 1988. The Theory and Efficiency for Forest Fire Analysis Using TM Images of Landsat. Developments of Remote Sensing Technology, 1988, No. 3.

FIG 3. Entire fire scene on the digital mosaic color-composite image using Landsat-5 TM 7, TM 4, TM 3 of 23, May 30 and June 6.

FIG 4. The landsat image shows the eastern section of fire field.

EXPERTS GROUP OF CHINA STATE COUNCIL. 1988. The Reports Assembly of Investigation on Forest Resources Recovery and Fire Ecological Environment in 1987, Daxinganling Extreme Fire Area. China Forestry Press, 1988.

JIN K.C. AND XIAO G.W. 1984. The Survey of Forest Fuel Geographic Distribution in the Daxinganling Region. Forest Fire Control, 1984, No. 1-2.

YANG YUN-QUIN 1981. Application of Satellite Image on Measuring Fire Area and Estimating Forest Losses. The 2nd National Remote Sensing Conference. July 1981. China.

YANG YUN-QUIN AND JIN JI-ZHONG. 1982. Application of Satellite Image on Forest Fire Control. Forest Science and Technology. No. 2, Feb. 1982. China

YANG YUN-QUIN AND THE OTHER. 1983. Application of Satellite Image on Fire Fuel Classification. In 3rd National Remote Sensing Conference. Oct. 1983. China.

YANG YUN-QUIN. 1985. Remote Sensing and Forest Protection. In 4th National Remote Sensing Conference. Nov. 1985. China.

WANG ZHENGFEI 1988. Outbreak, Development and Extinction of the Super-intensive Forest Fire in the North Great Xingan Mountains and Its Future Counter-measures. Journal of Ecology. Vol. 7 (sup.) 1988, pp. 26-29.

ZHAO X.Y. 1988. Speech on the Anniversary of the Daxinganling Extreme Forest Fire. Forest and Human. 1988, No. 5.

A Historical Perspective of Forestry in Canada

J.C. MERCIER
Deputy Minister, Forestry Canada

Mr. Chairman, Ladies and Gentlemen, it is a pleasure for me to speak to you tonight. I would like to add my words of welcome to you all, and especially to those of you who are visiting Ottawa for the first time.

If you have taken the time to explore the city, you may have come across evidence of its origins in the forest industry. But here in downtown Ottawa, surrounded by government buildings, it is not always easy to remember that this was once a lumber town.

The first permanent settler here was a Massachusetts lumberman named Philemon Wright, who, back in 1800, established a sawmill across the river.

In those days, the Gatineau Hills were covered with pine forests. It is, I suppose, an indication of the industriousness of Wright and those who followed him that the pine trees are long gone. From the windows of your hotel rooms, many of you will have observed the budding of the mature stands of maples that now cover what has become Gatineau National Park.

Fire has been a part of the legacy of the lumber industry in Ottawa.

In the 1830s, a fire in the nearby forests threatened to wipe out the village that was growing along the river. The community was saved only when the wind shifted after the flames had reached the outskirts of the settlement.

In 1900, this city witnessed one of the most devastating fires in Canadian history. It began in Hull when an overheated chimney ignited an adjacent building, but when the spreading flames reached the lumber yards along the river, residents feared that the entire city would go up in smoke.

By the time the flames were subdued, 15,000 people were left homeless, and $10 million in property had been destroyed. That, I hasten to add, is $10 million in 1900 dollars.

Fire was one hazard the good citizens of Ottawa had to contend with as a result of being a lumber town. Another hazard was the lumbermen themselves.

In the early days of the lumber industry, the Ottawa valley had more than its fair share of frontier exuberance and disorder.

The Irish and French Canadian lumberjacks would come out of the camps after a long winter, and the taverns would be the scenes of celebrations that are a far cry from the present-day decorum of the National Art Center.

Ottawa became notorious for its brawls and the pitched battles between rival factions of lumbermen.

I suppose the only thing that comes close to the boisterousness of those days is the occasional convention we host for lumbermen, foresters, or fire and forest meteorologists.

Ottawa remained a lumber town long after it became a government centre. Our fathers of confederation had to pick their way past stacks of sawn lumber and piles of sawdust on their way to work during the early years of our nation. From the parliament buildings, they could watch the great rafts of squared timber floating down the river.

The days of the timber rafts are gone. The street names remain to commemorate such industry pioneers as Eddy, Bronson, Sparks and Booth, but there is little that remains to remind us of how forestry once dominated this city.

The theme of your conference is a changing environment, with an emphasis on new technologies and concerns.

How do the technologies and concerns of the early days of the forest industry compare to the issues that you have been discussing in the past few days?

The problem of forest fires occupied the attention of both the lumber industry in Ottawa and the government for generations.

In 1871, Canada's first Prime Minister, Sir John A. MacDonald, wrote that, "the sight of the immense masses of timber passing my windows every morning constantly suggests to my mind the absolute necessity there is for looking at the future of this great trade..."

"The quantity of timber reaching Quebec is annually decreasing," he wrote, "and the fires in the woods are periodically destroying millions of dollars."

Among the measures he recommended was a joint commission of Ontario and Quebec to examine "the best way of protecting the woods from fires."

In 1906, the lumber baron J.R. Booth predicted that, "if fires were kept out, we'd have more timber 100 years from now than we did 50 years ago." Booth estimated that for every tree harvested, twenty more were destroyed by fire.

Sir Wilfrid Laurier, who was Canada's Prime Minister at the turn of the century, gives us one of the most intriguing looks at the techniques and concerns of fire prevention in his day.

For those of you who have come up from the states, I will point out that it is Laurier's picture that graces our five dollar bill, and his statue looks out over the crocuses near where Wellington Avenue crosses the Rideau Canal.

Wilfrid Laurier was an amazingly erudite and widely accomplished man. At the Canadian Forestry Convention of 1906 -- a forerunner of conferences such as this -- he could speak from the heart and from his own personal knowledge on a number of topics familiar to foresters today.

He talked about the importance of forests to watersheds. He spoke of the urgent need for reforestation, and advocated that, "trees are a crop like any other growth."

His audience applauded him for imparting a little silviculture advice passed on to him by a local lumberman. Plant a crop of pine among poplars, he advised, so that, "the pines, in their efforts to reach sunlight, will grow tall and without limbs."

The demands placed upon our political leaders, as well as the evolution of forestry into a complex science, have ended the days when a nation's prime minister could lecture a forestry conference on silviculture.

And similarly, the methods used to combat fire have changed since Laurier's time. As well, some of the causes of forest fires have changed.

One of the major causes of fires at the turn of the century was cinders from railway locomotives igniting forests along the rail lines.

In his speech to the forestry convention, Laurier praised the initiative of some railway managers who had installed screens on locomotive smokestacks. He advised railway companies to place extra patrolmen along the tracks to suppress the blazes that would inevitably flare up.

We have come a long way since the days when surveillance meant placing extra patrols along railway tracks.

What has not changed since Laurier's day is the concern over the economic waste inflicted by fire.

On average, some 9,000 forest fires burn about 2 million hectares in Canada every year based on a 10-year average.

That is about one-half of one percent of our national forested area. Some years, fires have consumed as much as 5 million hectares.

Each year, the forest industry in Canada logs close to a million hectares. Our ratio of burning-to-logging stands at 2 to 1 on average, and has gone as high as 5 to 1.

J.R. Booth, you will recall, estimated the burning-to-logging ratio in his day may have been even higher than 20 to 1. He would have had no way of knowing what impact lightning fires were having on the distant, unsettled regions of the northwest, so we can assume that the ratio was, in fact, much higher than 20 to 1.

Our forest industries have grown since Laurier's day, but our surveillance, pre-suppression, and suppression abilities have grown as well.

Another thing that has not changed since Laurier's time is the importance of the forest industry in this country.

The lumber and pulp and paper industries are the bedrock of our economy today, just as they were in Laurier's time.

In 1987, forestry employed approximately 289,000 Canadians directly and contributed $41 billion (value of shipment) to the Canadian economy. Over 350 communities from coast to coast depend entirely on forestry as their means of livelihood.

Our exports of forest products in 1987 amounted to almost $21 billion. Forestry is a towering giant in Canada's export trade, and one of the most significant factors in our favourable trade balance.

And the importance of forestry to Canadian trade is not likely to diminish in the years ahead. In fact, we anticipate that the dollar value of our exports in forest products will rise by 55% by the year 2010.

Forestry is an engine of growth throughout our economy. The industry spends, on average, $4.5 billion a year on repairs, modernization, and expansion. That kind of spending is felt in our industrial heartland, far from the forest stands.

What these figures tell us is that we have invested more value in our forests than would have been conceivable to past generations.

We have gone far beyond the simple measures that men like Laurier and Macdonald advocated to regenerate our forests.

Our silviculture facilities, reforestation programs, and the amount of investment in forest management, by our businesses, and our federal and provincial governments, would have staggered them.

Take the forest resource development agreements as one example. Over the past five years, a billion dollars of government money has been invested in forestry as a result of these agreements between the federal and provincial governments.

The private sector has been investing heavily as well, increasing the work of our forest resources.

As it upgrades its facilities to meet the demands for more value-added products, the forest sector will require even larger infusions of capital.

Some projections indicate that, between now and 1995, the industry will seek a total of almost $44 billion in capital investments.

Much of it will go toward retooling to meet the challenges of the next decades.

In Laurier's time, the forest industry could still cut its way through extensive stands of virgin timber. Other than in the minds of a few visionaries, little thought was given to managing the resource for the future. Little money was invested in finding better ways to process that timber into end products.

A tree is worth more to us today than it was in Laurier's time, because we have invested so much more into managing that tree, developing and marketing its products, and finding more efficient ways of turning it into paper or wood products.

As we have invested so much more money into our forest resources, we owe it to ourselves and to the generations to come to protect that investment.

The measures you have been discussing over the past few days can be compared to the fire insurance policy we in North America take out on our forests. It is our guarantee of protection for the future.

When a family increases the value of its home by renovation or expansion, it normally would also increase its fire insurance coverage.

Prudence demands that we continue to increase the amount of that protection as we continue to invest more and more money in our forest industries.

The annual cost of fire control in Canada, apart from assessing timber loss, has been estimated at $250 million.

Much of this cost arises from fire suppression. A very small portion can be ascribed to "fire insurance", which I would define in terms of the amount invested in forest fire research.

Investing in research reminds me of the words of the nobel laureate, Albert Szent-Gyorgyi: "Research is four things," he said: "Brains with which to think; eyes with which to see; machines with which to measure; and, fourth, money."

I am sure there is not a person in this room who believes enough money is available for necessary research into fire and forest meteorology.

Often it takes decades before money spent on research and development can show a favourable impact on the bottom line of the ledger. But in the area of fire research, we can already point to tremendous returns on investments.

Take, as an example, the research that has gone into creating the Canadian Forest Fire Danger Rating System.

A recent audit has shown that, since 1928 when we first began developing fire danger rating systems, we have invested $4.8 million in the fire weather index system. It has been estimated that this investment has resulted in a savings of $750 million for the forest industry in one decade alone.

That is an investment return of over 150 times the cost of establishing the fire danger rating system.

Add to that our other accomplishments in the area of fire and forest meteorology:

- The responsibilities we have undertaken in fire detection, including infrared technology, lightning locator systems, and sophisticated planning for aircraft patrol;
- The advances in field methods and physics involving both fuel moisture and fire behaviour;
- The advances made in pump and hose technology, and aerial ignition capability;
- The studies into fire ecology, and into the effect of fire on timber supply and the forest economy; and,
- The advances in the use of computerized information systems to apply the forest fire danger rating system to the tasks of surveillance, pre-suppression, and suppression.

They add up to a significant investment by the Federal Government in the insurance policy that will protect our forests for future generations.

From the beginning, when men like Jim Wright and Herb Beall pioneered forest fire research in Canada, we have developed a distinctly Canadian School of Forest Fire Science and Technology.

Our emphasis on empirical measurement of field data has proven particularly suited to Canadian forests and forestry.

We have made our advances in fire and forest meteorology on several levels of sophistication over a long period of time.

On one level, we have had pioneers like Jim Wright and Herb Beall putting a desk letter tray, containing fuels of known dry weight, on the forest floor. Dr. Wright called this precursor to the Duff Hygrometer, his "forest litter basket."

At another level, our contemporary scientists have applied theory and principles of mathematics and physics to fire behaviour prediction. Still others explore the use of artificial intelligence and expert systems for use in fire management decision-making.

Steadily, and in increments, we have been building up the insurance policy that protects Canada's investment in its forest resources.

Similar stories of advancing technology and the incremental growth of our knowledge about fire and forest meteorology could be told by each of you.

I hope you will excuse my seeming to blow my own department's horn, but what I wish to emphasize through all this is the importance of continuity.

Fighting forest fires has demanded the attention of North Americans for generations. Over the years, some very brilliant minds and energetic personalities have contributed to the effort.

These men and women have been able to build upon the achievements of their predecessors partly because new talent has always been drawn into this field, and partly because the pioneers have been on hand to train the young generation.

The theme of our conference is "New Technologies and Concerns."

Our technologies have changed because we have been able to build upon past achievements.

If our concerns have changed, it is because we have a more intimate understanding of such matters as the role of fire in the ecosystem, and the manner in which our knowledge can be applied by using leading-edge technologies.

We have also been able to move beyond the basic concerns of Laurier's day: though early detection and rapid initial attack remain the cornerstone of fire management practices, it is no longer sufficient simply to "place extra patrols along the railway tracks." Our concerns have broadened and deepened.

In the past days you have been discussing everything from spatially integrated radiation to 3-D diagnostic wind flow models.

From air toxics to the use of prescribed fire to control insects. From diurnal fine fuel moisture to the use of satellites for fire detection.

I think you have earned the right to take a great deal of pride in your profession.

Pride was a hallmark of the lumberjacks who used to come down from the shanties in the spring and take over this town with their festivity and exuberance.

Much of your time while in Ottawa has been spent discussing weighty matters. But, like the lumberjacks a century ago, I hope you have had an opportunity to get out into this city. Make it your own while you are here, just as the lumberjacks used to make it their own each spring.

It is a city that was built on the lumber trade. It is the capital city of a nation that continues to prosper from forestry.

Fire and forest meteorologists have played an important role in helping the forest industry to prosper, and you have earned the right to celebrate in a forestry town.

Thank you.

Une Perspective historique de la foresterie au Canada

J.C. MERCIER
Sous-Ministre de Forêts Canada

Monsieur le Président, Mesdames et Messieurs, c'est pour mois un immense plaisir de pouvoir m'adresser à vous ce soir. J'aimerais souhaiter la bienvenue à chacun de vous et plus particulièrement à ceux qui visitent Ottawa pour la première fois.

Si vous avez pris le temps d'explorer un peu les environs, sans doute aurez-vous remarqué qu'Ottawa puise ses origines dans l'industrie forestière. Au coeur même de la ville, encerclé de toutes parts par les bâtiments du gouvernement, il n'est pas toujours facile de se rappeler qu'il s'agissait autrefois d'un village de bûcherons.

Le premier colon à s'établir ici venait du Massachussets. Il s'agissait d'un bûcheron appelé Philemon Wright qui, vers les années 1800, décida de construire une scierie de l'autre côté de la rivière.

À l'époque, les collines de la Gatineau étaient couvertes de forêts de pin. M. Wright et ceux qui l'ont suivi étaient sans doute très laborieux, à preuve les pins ont disparu depuis longtemps. Depuis vos chambres d'hôtel, beaucoup d'entre vous pourront observer les peuplements mûrs d'érables qui bourgeonnent sur les collines formant désormais le parc fédéral de la Gatineau.

Avec l'industrie du bois, le feu fait partie de l'histoire d'Ottawa.

Au cours des années 1830, un incendie dans les bois voisins menaça de raser le village qui avait pris naissance en bordure de la rivière. Ce dernier ne fut sauvé que parce que le vent tourna au moment même où les flammes parvenaient aux extrémités de la bourgade.

En 1900, Ottawa connut l'un des incendies les plus dévastateurs de l'histoire du Canada. La conflagration débuta à Hull par la propagation d'un feu de cheminée au bâtiment adjacent. Lorsque les flammes atteignirent les réserves de bois qui s'empilaient le long de la rivière, les habitants se mirent à craindre la complète destruction de leur ville.

Quand on réussit enfin à maîtriser l'incendie, 15000 habitants avaient perdu leur foyer et le feu avait détruit pour 10 millions de dollars de biens. Je m'empresse de préciser qu'il s'agissait de dollars de 1900.

Vivant de l'industrie du bois, Ottawa devait tenir compte du feu dans sa planification. Un autre danger venait des bûcherons eux-mêmes.

En effet, au début de l'industrie forestière, la vallée de l'Outaouais avait plus que sa juste part de ces robustes gaillards au tempérament bouillant qui faisaient reculer nos frontières.

Après un long hiver, les bûcherons irlandais et canadiens français quittaient les camps pour envahir les tavernes et se lancer dans des libations qui n'avaient aucune commune mesure avec le genre de réception que l'on peut voir aujourd'hui au Centre national des arts.

Ottawa se tailla une véritable réputation pour ses bagarres et ses rixes entre factions rivales de bûcherons.

Je suppose que la chose qui se rapproche le plus de la folle ambiance qui régnait en ces jours anciens est le colloque occasionnel où nous accueillons bûcherons, forestiers ou spécialistes des incendies de forêt et de météorologie forestière.

Ottawa a gardé sa vocation forestière longtemps après être devenu un centre gouvernemental. Lorsque notre nation en était à ses balbutiements, les pères de la confédération devaient se frayer un chemin entre les tas de sciure et de bois pour se rendre au travail. De leur bureau au Parlement, ils pouvaient voir les vastes trains de bois descendre la rivière.

Ces temps sont désormais révolus et seul le nom des rues comme Eddy, Bronson, Spark ou Booth commémore les pionniers de l'industrie forestière. Très peu de traces nous rappellent que cette ville était avant tout dominée par le bois.

Vous avez choisi pour thème du colloque l'environnement en évolution et décidé de mettre l'accent sur les nouvelles technologies et les nouveaux problèmes.

Comment peut-on comparer les technologies et les problèmes des premiers âges de l'industrie forestière à ceux sur lesquels vous vous êtes penchés au cours des derniers jours?

Pendant des générations, l'industrie du bois d'Ottawa et le governement ont étudié le problème des feux de forêt.

En 1871, le premier Premier Ministre canadien, Sir John A. MacDonald écrivait: "la vue des immenses masses de bois qui passent devant ma fenêtre tous les matins me rappellent constamment l'absolue nécessité de sonder l'avenir de cette grande industrie..."

"La quantité de bois qui parvient au Québec diminue chaque année", écrivait-il, "et les feux de forêt détruisent périodiquement des millions de dollars de bois."

Parmi les mesures qu'il recommandait se trouvait la constitution d'une commission mixte de l'Ontario et du Québec pour trouver "la meilleure façon de mettre le bois à l'abri du feu".

En 1906, le magnat du bois J.R. Booth prédisait que "si on parvenait à empêcher les feux de forêt, il y aurait plus de bois dans un siècle qu'il y en avait 50 ans plus tôt". Selon lui, pour chaque arbre abattu, le feu en détruisait vingt ou davantage.

Sir Wilfrid Laurier, Premier Ministre du Canada au début du vingtième siècle, nous donne un aperçu pour le moins intrigant des techniques de lutte contre le feu et des craintes qui existaient à pon époque.

Pour ceux qui viennent des États-Unis, je précise que le portrait de Laurier orne notre billet de cinq dollars et que la statue de ce grand homme surplombe les crocus à l'endroit où l'avenue Wellington traverse le canal Rideau.

Wilfrid Laurier était un remarquable érudit, un homme cultivé en tout. Il pouvait donner son point de vue personnel et tirer à même son expérience pour discourir sur divers sujets familiers aux forestiers d'aujourd'hui, comme il le fit au colloque de foresterie de 1906, précurseur de nos colloques modernes.

À cette occasion, il souligna l'importance des forêts pour les bassin hydrographique et le besoin urgent de reboiser, tout en ajoutant que "les arbres sont une culture comme une autre."

Son auditoire l'applaudit quand il donna un petit conseil de sylviculture que lui avait confié un bûcheron de sa connaissance. "Plantez quelques pins entre des peupliers", expliqua-t-il. "Les pins, en essayant de parvenir jusqu'au soleil, pousseront haut et sans branches."

Les demandes auxquelles sont astreints nos dirigeants politiques et l'évolution de la foresterie, une science désormais fort complexe, ont mis fin aux jours où le Premier Ministre d'un pays pouvait faire un exposé sur la sylviculture à l'occasion d'un colloque de foresterie.

De même, les méthodes utilisées au temps de Wilfrid Laurier pour lutter contre le feu ont changé, et avec elles certaines causes à l'origine des incendies de forêt.

Au début du siècle, l'une des principales causes de ce fléau était les cendres qui s'échappaient du fourneau des locomotives et mettaient le feu aux forêts le long des voies de chemin de fer.

Dans le discours qu'il donna au colloque de foresterie, Laurier félicita certains directeurs de société ferroviaire pour avoir posé un écran sur la cheminée des locomotives. Il leur conseilla d'augmenter le nombre de patrouilles le long des voies afin d'éteindre les débuts d'incendies inévitables.

Nous avons parcouru beaucoup de chemin depuis ces jours où la surveillance des incendies signifiait un surcroît de patrouilles le long des voies de chemin de fer.

Le problème des pertes économiques entraînées par le feu, lui cependant n'a pas changé.

Une étude de 10 ans a révélé qu'en moyenne, 9000 incendies de forêt détruisent chaque année environ 2 millions d'hectares de bois au Canada.

Ceci équivaut à la moitié d'un pour cent des terres boisées du pays. Certaines années les feux détruisent jusqu'à 5 millions d'hectares de forêt.

Par ailleurs, l'industrie forestière canadienne exploite annuellement près d'un million d'hectares de forêts. Le rapport entre le feu et l'abattage se situe donc en moyenne à 2 pour 1. Il monte parfois jusqu'à 5 pour 1.

J.R. Booth, je le rappelle, fixait ce rapport au-dessus de 20 pour 1 à son époque. Rien ne lui permettait de déterminer l'impact des feux de forêt causés par la foudre dans les régions du nord-ouest, alors non colonisées. On peut donc présumer que le rapport était en réalité beaucoup plus élevé.

Notre industrie forestière a considérablement évolué depuis l'époque de Laurier, mais nos capacités en matière de surveillance, de prévention et d'extinction des feux ont grandi également.

L'importance de l'industrie forestière pour le Canada n'a pas beaucoup changé elle non plus depuis Laurier.

L'industrie du bois et celle de la pâte et papier constituent la base même de notre économie, comme à l'époque de ce premier ministre.

En 1987, la foresterie occupait directement 289000 Canadiens environ et avait injecté 41 milliards de dollars (valeur des expéditions) dans l'économie nationale. Plus de 350 communautés du Canada vivent entièrement du bois.

La même année, nos exportations de produits forestiers se sont chiffrées à près de 21 milliards de dollars. La foresterie fait figure de géant parmi les secteurs d'exportation du Canada. C'est aussi l'un des facteurs qui contribuent le plus à notre balance commerciale positive.

Il est peu probable que la foresterie voie son rôle dans les échanges commerciaux du Canada s'affaiblir au cours des années à venir. Nous prévoyons au contraire que la valeur des exportations de produits du bois augmentera de 55% d'ici l'an 2010.

La foresterie contribue à la croissance de l'économie dans son entier. Cette industrie dépense en moyenne 4,5 milliards de dollars par année pour les réparations, la modernisation et l'expansion. Des dépenses de cet ordre ont des effets qui débordent du secteur forestier proprement dit et touchent toutes les industries.

Ces chiffres montrent que nous avons investi beaucoup plus dans la forêt que ce que les générations passées auraient pu imaginer.

Nous avons dépassé depuis longtemps les moyens rudimentaires auxquels songeaient Laurier et MacDonald quand ils préconisaient la régénération des forêts.

Nos installations sylvicoles, nos programmes de reboisement et les sommes injectées dans l'aménagement forestier par les entreprises, le gouvernement fédéral et les provinces les laisseraient tout simplement pantois.

Prenez les ententes sur le développement des ressources forestières par exemple. Au cours des cinq dernières années, ces ententes entre le gouvernement fédéral et les provinces ont nécessité l'investissement d'un milliard de dollars en deniers publics dans la foresterie.

Le secteur privé n'est pas demeuré en reste, ce qui a accru la valeur de ces ressources.

Le secteur forestier aura besoin de capitaux encore plus importants pour perfectionner ses installations afin de répondre à la demande de produits à plus grande valeur ajoutée.

Certains prévoient que d'ici 1995, l'industrie aura besoin de près de 44 milliards de dollars en immobilisations.

Une bonne partie de cette somme ira au remplacement du matériel face aux défis que nous réservent les décennies à venir.

À l'époque de Laurier, les entreprises forestières disposaient d'immenses peuplements jusqu'alors intouchés. Seuls quelques visionnaires avaient émis l'idée d'une exploitation raisonnée de cette ressource en prévision de l'avenir. On investissait relativement peu dans la recherche de meilleures méthodes pour transformer les grumes en produits finis.

De nos jours, un arbre vaut beaucoup plus cher qu'à l'époque de Laurier, en raison des énormes sommes investies dans les soins apportés à cet arbre, dans la création et la mise en marché des produits et dans la recherche de meilleures méthodes pour fabriquer du papier ou des produits du bois.

L'importance même de cet investissement nous oblige à le protéger pour nous comme pour les générations à venir.

Les mesures dont vous avez discuté ces derniers jours pourraient être comparées à une assurance-feu pour les forêts d'Amérique du Nord. Il s'agit d'une garantie de protection pour l'avenir.

La plupart du temps, celui qui accroît la valeur de sa maison en la rénovant ou en l'agrandissant augmente aussi la couverture de son assurance.

La prudence exige que nous continuions d'améliorer cette protection en investissant dans l'industrie forestière.

Au Canada, la lutte contre les feux de forêt coûte environ 250 millions de dollars, sans tenir compte des pertes attribuables à ce fléau.

La majeure partie des coûts vient de l'extinction des incendies. L'assurance proprement dite, c'est-à-dire la somme investie dans la recherche sur les feux de forêt, coûte relativement bon marché.

Investir dans la recherche me rappelle les mots du prix nobel albert szent-gyorgyi: la recherche se compose de quatre choses", "le cerveau sans lequel l'homme disait-il, ne pourrait penser, les yeux qui lui permettent de voir, les machines qui l'aident à mesurer et l'argent."

Personne dans cette pièce, j'en suis sûr, n'est prêt à dire qu'on dépense suffisamment pour entreprendre les recherches nécessaires sur les feux de forêt et la météorologie forestière.

Il faut souvent plusieurs décennies avant que les sommes investies dans la recherche et le développement se traduisent par un bénéfice calculable noir sur blanc. Cependant, on constate d'ores et déjà que l'argent investi dans la recherche sur les feux de forêt rapporte énormément.

Il suffit de penser à la recherche qui a débouché sur la mise au point de la méthode canadienne d'évaluation des dangers d'incendie de forêt.

Selon une analyse récente, on a investi 4,8 millions de dollars dans ce système qui indexe les risques d'incendie selon les conditions météorologiques, depuis ses débuts. Pourtant, cet investissement a permis à l'industrie forestière d'économiser 750 millions de dollars en l'espace d'une décennie.

Il s'agit là d'un rapport qui dépasse 150 fois le coût de mise en place du système.

Il faut ajouter à cela d'autres réalisations dans le secteur des feux de forêt et de la météorologie forestière:

- Les recherches entreprises pour détecter les feux de forêt, notamment les méthodes infrarouges, les techniques de localisation des orages et les systèmes de planification complexes des patrouilles aériennes;
- Les progrès réalisés dans les méthodes pratiques et la physique relatives au comportement du feu et à la teneur en eau des combustibles;
- L'avancement des techniques propres aux pompes et aux tuyaux ainsi qu'à l'allumage par voie aérienne;
- Les études sur la pyro-écologie ainsi que celles relatives à l'incidence du feu sur les réserves et l'économie forestières; et
- Les progrès accomplis dans le recours aux systèmes d'information électroniques en vue de l'application de la méthode d'évaluation des dangers d'incendie à la surveillance, à la préparation, à la lutte et à l'extinction des feux.

Tout cela représente un investissement majeur du gouvernement fédéral dans l'assurance qui nous aidera à protéger nos forêts pour les générations qui nous succéderont.

Dès le début, lorsque des hommes comme Jim Wright et Herb Beall ont lancé la recherche sur les feux de forêt au Canada, est née une école typiquement canadienne des sciences et de la technologie dans ce domaine.

L'intérêt accordé à l'évaluation empirique des données sur le terrain convient particulièrement bien aux forêts et à la foresterie au Canada.

Les progrès réalisés au chapitre des feux de forêt et de la météorologie forestière ont porté sur plusieurs paliers au cours d'une longue période de temps.

Au premier palier se trouvaient les pionniers comme Jim Wright et Herb Beall qui déposaient sur le sol en forêt des corbeilles à papier remplies de combustibles au poids sec connu. Wright appelait ce précurseur de l'hygromètre duff sa "corbeille à papier forestière".

À l'échelon suivant, des chercheurs contemporains se sont tournés vers la théorie et les principes de mathématique et de physique pour prévoir le comportement du feu. D'autres encore songent à recourir à l'intelligence artificielle et aux systèmes d'exportation dans le processus décisionnel relatif à la gestion des incendies.

Lentement, mais sûrement, se développe la police d'assurance qui préservera ce que le Canada a investi dans ses ressources forestières.

Chacun d'entre vous a sans aucun doute des histoires analogues de progrès techniques et d'avancement des connaissances à raconter sur les feux de forêt et la météorologie forestière.

Vous m'excuserez si je semble faire preuve de vantardise en parlant des réalisations de mon ministère. Le but recherché est surtout de souligner l'importance d'une continuité.

La lutte contre les feux de forêt mobilise les nord-américains depuis plusieurs générations. Au fil des ans, des hommes particulièrement brillants et énergétiques ont contribué à la tâche commune.

Si ces hommes et ces femmes ont pu bâtir sur les réalisations de leurs prédécesseurs, c'est que le domaine a su attirer des personnes compétentes et que les pionniers ont aidé à formation de la relève.

Votre colloque a pour thème les nouvelles technologies et les nouveaux problèmes.

La technologie a évolué parce que nous sommes parvenus à tirer parti de ce qui avait été réalisé dans le passé.

Si les problèmes ont changé, c'est que nous connaissons beaucoup mieux certains aspects de la question comme le rôle du feu dans l'écosystème, et savons comment ces connaissances peuvent être mises en pratique par des techniques à la fine pointe du progrès.

Nous avons également dépassé les problèmes fondamentaux auxquels se heurtait Laurier: si la détection et une réaction rapides demeurent la pierre angulaire des pratiques en matière de gestion du feu, "mettre des patrouilles supplémentaires le long des voies de chemin de fer" ne suffit plus désormais. Nos problèmes se sont élargis et approfondis.

Au cours des derniers jours, vous avez discuté de beaucoup de choses, de l'intégration spatiale du rayonnement aux modèles tridimensionnels permettant de prévoir la direction du vent. Des composés toxiques dans l'air à l'utilisation du brûlage dirigé pour lutter contre les ravageurs. Des combustibles critiques diurnes à l'emploi de satellites pour la détection des feux de forêt.

Je pense que vous avez le droit d'être fiers de votre profession.

La fierté était un des traits caractéristiques des bûcherons qui quittaient leur camp au printemps et envahissaient la ville pour y faire ripailles.

Vous avez consacré une bonne partie de votre séjour à Ottawa à l'étude de questions sérieuses. J'espère cependant qu'à l'instar des bûcherons d'autrefois, vous aurez la possibilité de visiter la ville. Tirez le meilleur parti de votre séjour à Ottawa, comme ils le faisaient chaque printemps.

C'est une ville née du bois. C'est aussi la capitale d'un pays dont la prospérité continue de s'appuyer sur la foresterie.

Les spécialistes en feux de forêt et en météorologie forestière ont joué un rôle déterminant dans l'essor de cette industrie. Vous vous êtes mérité le droit de le célébrer dignement dans une ville qui a son origine dans la forêt.

Je vous remercie de votre attention.

The Climatic Background and Weather Conditions of 1987 Daxinganling Extreme Forest Fire in China

YANG YUN-QIAN AND JIN JI-ZHONG
Heilongjiang Forest Protection Research Institute
Harbin, People's Republic of China

Abstract

This report describes an enormous forest fire which occurred in the northern part of the Daxinganling forest region in Heilongjiang province of China on May 6 to June 2 in 1987. The fire burned 1.33 million ha.

The report investigates the climatic background and synoptic weather conditions affecting the fire. The fire occurred after a two year drought in the area. In 1986, the precipitation was 30-40% below the annual mean. In March and April 1987, the relative humidity was less than half the historical mean for the identical period.

The upper air flow and surface weather pattern on the days prior to the fire and during the fire were analyzed. There was a deep north-south trough lying over 100°E longitude on May 6. On May 7 this trough split into two, forming a northern trough and a southern trough. The northern trough moved over north-eastern China. It resulted in a strong 'dry' cyclone. The extreme high temperature and low relative humidity together with the strong surface wind field created an intense crown fire with spotting. During the fire period a persistent upper front zone was lying west-east over northern China. The upper trough moved fast. The surface weather characteristics included little precipitation, rapid variation of the wind directions, and minimum relative humidity less than 25%. All of these factors were conductive to the spread and persistence of the fire.

The Canadian Forest Fire Danger Rating System was used to analyze the fire. The results of the analysis imply that the Canadian system is well suited to the Daxinganling region fire situation.

In the discussion some potential studies in China for fire weather prediction are presented.

Résumé

Ce rapport décrit un incendie de forêt énorme qui a eu lieu dans la pártie nord de la region forestière Daxinganling dans la province Heilongjiang de la Chine du 6 mai au 2 juin 1987. 1,33 million ha ont brûlés pendant cet incendie.

Ce rapport étudie les conditions synoptiques de la météo et l'arrière-plan climatique qui ont affectés l'incendie. Le feu s'est produit après deux ans de sécheresse dans cet endroit. La precipitation en 1986 était 30-40% dessous la moyenne annuelle. En mars et avril 1987, l'humidité relative était moins d'une denie la moyenne historique pour la période identique.

La circulation de l'air en altitude et les tendances de la météo à la surface des jours avant et durant le feu ont été analysées. Il y avait un creux barométrique nord-sud profond situé à 100°E de longitude le 6 mai. Le 7 mai ce creux barométrique s'est divisé en deux, formant un creux barométrique nord et un creux barométrique sud. Le creux barométrique nord s'est déplacé au nord-est de la Chine et le résultat fut un cyclone "sec" et fort. L'extrême température élevée et l'humidité relative basse ensemble avec le champ de vent du surface fort ont crées un feu de cime à des endroits. Pendant la période du feu une zone persistonte de front en altitude se situait de l'ouest à l'est au nord de la Chine. Le creux barométrique en altitude voyagea rapidement. Les caractéristiques de la météo à la surface inclurent peu de précipitation, une variation rapide des directions du vent et une humidité relative minimum de moins de 25%. Tous ces facteurs ont menés à la propagation et la persistance du feu.

La méthode canadienne de l'évaluation des dangers d'incendie de forêt a servi afin d'analyser le feu.

Les résultats de l'analyse laissent sous-entendre que la méthode canadienne est adéquate pour evaluer la situation de l'incendie de la région de Daxinganling.

Des études potentielles pour la prédiction de la forêt-météo on Chine sont présentées à l'intérieur de cette discussion.

Introduction

An enormous forest fire disaster occurred in the northern part of the Daxinganling forest region in Heilongjiang province of China on May 6, 1987. It was put out on June 2 after 28 days of suppression efforts.

This extreme fire brought heavy losses. The fire area was 1.33 million ha and the forest area blackened was 1.14 million ha, with damage to 870,000 ha of forest. The fire killed 193 people, injured 226, and left 56,092 homeless. The great fire, without precedent

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

in China's forest fire history, became a focus of world attention.

1. DESCRIPTION OF THE DAXINGANLING FOREST REGION

The 8.4 million ha Daxinganling region is located in the extreme northeastern portion of China, between 50°30'N and 53°30'N, 121°30'E and 127°E. The region is bounded on the north by the U.S.S.R. along the Heilongjiang River. The main geographic feature is the Great Xingan mountains with elevations ranging from 450 m to 1100 m in the northern portion of the region and rolling hills from 300 m to 500 m in the south.

The vegetation in the forest fire area of the Great Xingan Mountains belongs to the cool climatic deciduous and coniferous forests. The vegetative types are Dahurian larch forest, Mongolian Scotch pine forest, Birch forest and Tundra-bog vegetation as Figure 1 shows (Zhao Dachang 1988).

The Daxinganling is a high fire occurrence region, with a mean annual burned area of woodland of 144,000 ha and a mean annual burned area of 1.92%. Forest fires mainly occur in the southeast xylosma-birch secondary forest. On average, 67.1% of fires are human-caused and 32.9% lightning-caused (excluding the unknown-caused fires). Only 2.2 extreme fires occur per year, 5.2% of the total fires, but are responsible for 95.5% of the total burned-area. (Lou Yuhai and Wang Souxin 1988).

In the area of the 1987 fire there had been no large fires for quite a few years. Accumulations of cured grasses, dead and drying trees, logging slash and litter, formed a great fuel bed for the fire. According to a rough investigation in six forest districts, the fuel loads were 57.0 t/ha on the southern slopes, 61.3 t/ha on hill tops, 55.6 t/ha on the northern slopes (Jin K.C. and Xiao K.W. 1984).

2. THE 1987 DAXINGANLING FIRE CHRONOLOGY

Multiple fires occurred in the northern portion of Daxinganling region on May 6. After fire fighting, four fires still remained burning on May 7. Figure 2 shows the locations of the four fires, at Gulian, Hewan, Yixi and Pangu. The four fires totalled 28,000 ha in size on the morning of May 7. In the evening of May 7, a strong cold front invaded this area with wind gusts of 30-50 km/h, creating extreme fire behaviour. The Gulian fire reached Xilinji at 2020 hours. Thirty minutes later the fire spread eastward into Tuqiang, which is 30 km from Xilinji. By 0010 hours of May 8 the fire had spread 70 km to the east. Within 5 hours, three towns in which there were headquarters of forestry enterprises, seven forest farms and four and half wood yards had been destroyed. On May 8 1230 hours the total fire area had reached about 0.43 million ha (calculated from NOAA imagery). The fires did not respond to any control efforts. On May 13, about 29 intense fire lines, totalling 91 km in length, and hundreds of hot spots had been scattered in two major fire areas. Fifty thousand soldiers and local residents were fighting the fires. By May 25 the fire was under control, aided by 7.8 mm of rain. On June 2 every spark was extinguished and the last wisp of smoke disappeared. The authorities declared that the tremendous fire was out.

On the evening of May 7, according to a calculation from Landsat imagery, the maximum temperature of the fire reached 1,000°C (Dai Chang-da 1988). The strong convection column with spotting and crowning appeared in the fire area. Fire-breaks, hundreds of meters wide, could not stop the spreading fire.

Climatic Background Prior to the Fire

1. GENERAL CLIMATOLOGY

This is the coldest region in China. It belongs to the continental cold-temperature climate zone with long cold dry winters and short warm humid summers. The temperatures range from -35°C to 18°C with a annual mean temperature of -3°C to -5°C . The minimum temperature recorded was -53°C. Precipitation varies from 350 mm to 600 mm with an annual mean value of 450 mm. The period of snow cover exceeds 4 months. The depth of snow usually is 30-50 cm inside the forest. The fire season occurs from March 15 to the end of June, the fall fire season from September 15 to early November. During the two fire subseasons, cyclonic activity produces frequent strong winds. The fire season is the driest period in the year causing many fires particularly in the spring.

2. ANALYSIS OF FIRE CLIMATIC DATA

The analysis of the climatic data for six weather stations (Figure 3A) shows that extreme fire potential had existed in the region for two years.

A. *Precipitation*

As table 1 indicates: (1) The annual mean precipitation for Mohe, Amur, Tahe is 422 mm, 447 mm, 475 mm respectively. In 1985 Mohe and Huzhong appeared as two negative centers of annual anomalies, -38 mm and -86 mm. In 1986 the precipitation for Mohe, Amur, Tahe was reduced to 76%, 57%, 67% of normal, minimum values for the past 10 years. In 1986 the maximum negative anomaly was by Amur with a remarkable -192 mm as shown in Figure 3B. (2) In 1987 the accumulated precipitation from January to April geographically was a minimum amount area, namely Amur as shown in Figure 3C. (3) In April 1987, the precipitation at Mohe and Amur was only 34% of the historical mean value as shown in Figure 3D. In the early spring the Daxinganling region usually has 50 cm of snow, but in the spring of 1987 the snow cover was only about 15 cm deep. The prolonged drought within the past two years and the recent decrease in precipitation occurred in the

Table 1. Precipitation (mm)

Weather Station No. Name	Annual Mean	1985 Anomaly	1986 Anomaly	1987 Jan.- April	His. April	1987 April Over His.	Ratio of 87' April
1 Mohe	422	-38	-104	21.8	20.4	7.0	34%
2 Amur	447	-30	-192	19.3	22.7	7.8	34%
3 Tahe	475	+63	-159	49.1	28.1	21.9	78%
4 Huzhong	482	-86	-99	52.9	26.0	40.7	157%
5 Xinlin	503	-24	-181	51.9	30.9	31.8	103%
6 Jiagedaqi	491	+47	-14	29.1	28.0	14.0	50%

Table 2. Temperature (°C) and Relative Humidity (%)

	TEMPERATURE				RH	
Weather Station No. Name	Annual Mean	1986 Anomaly	History April Mean	1987 April Anomaly	1986 Sept. to Dec. CARH	1987 Mar. to April CARH
1 Mohe	-4.7	+1.1	-0.6	-1.4	-14	-50
2 Amur	-5.2	+0.8	-0.6	-1.6	-20	-48
3 Tahe	-2.8	+0.9	+0.6	-1.4	-24	-46
4 Huzhong	-4.4	+0.7	-0.1	-1.8	-9	-19
5 Xinlin	-3.3	+0.9	+0.2	-1.1	-25	-28
6 Jiagedaqi	-1.3	+0.8	+2.2	-1.2	-15	-35

identical area, Amur, in which the potential fire situation had been quite severe (Fig. 3B, 3C, 3D).

B. Temperature

Table 2 shows the annual mean, 1985 mean, 1986 mean of temperature. In 1986, throughout the Daxinganling region the mean temperature exceeded the annual mean by 0.7°C, particularly 1.1°C in Mohe (Figure 3E).

C. Relative Humidity

Table 2 shows a value for the cumulative anomaly of mean RH (CARH), within six 10-day periods for September-December 1986 and March-April 1987. The CARH value was negative for all six stations. The CARH of Mohe and Amur approached -50 (Figure 3F). It indicates that the winter of 1986 and the spring of 1987 had been very dry due to lack of precipitation (Yi Qing-ju 1988)

Low precipitation, higher cumulative temperatures, low humidity and limited green-up of living fuel created great potential flammability for the large amount of forest fuel.

Synoptic Weather Conditions for the 1987 Extreme Fire Occurrence

Short term weather conditions govern the fuel moisture content. It creates suitable conditions for fire ignition and determines the rate of spread.

1. THE UPPER PATTERN

The upper pressure pattern over eastern Asia was dominated by a trough-ridge-trough pattern, one trough at 140°E and another at 100°E. On May 6, 2000 hours, a cold air mass centered over the Novaya Zemlya Islands in Barents Sea (60°E, 75°N) continued to supplement cold advection into the north-south great-scale trough located at 100°E, 50°N. It resulted in intensification of warm advection in the east part of the trough and strengthened the negative eddy of thermal wind. Then a warm ridge developed significantly. On May 7, the trough at 100°E was split apart into two troughs, a northern trough and a southern trough while the trough was moving. In the evening of May 7 the northern trough caused a surface cold front to sweep across north-eastern China which brought about a strong synoptic weather system. Figures 4A, 5A, 6A show the moving troughs at 70 kPa on May 6, 2000 hours to May 8, 2000 hours.

2. THE SURFACE WEATHER PATTERN

On May 6, the cold air mass over 100°E was strengthened and moved eastward. The cold front pressed on towards Mohe by 1400 hours of May 7. The northern wind behind the cold front gusted -0.12 kPa/h in Mohe-Amur at 800 hours to 1400 hours. Meanwhile the rate of rising temperature reached maximum 6°C/h. Strong convergent conditions were present in the lower atmospheric layer. On May 7, the four fires were in the warm sector preceding the cold front. As the cold front arrived in the evening, these fires became very active with fire whirls where the shear of wind was significant. Figures 4B, 5B, 6B shows the activity of the surface front on May 6 1400 hours to May 8 0200 hours. According to the reading of Amur station the maximum wind speed was 61.2 km/h at 2326 hours of May 7.

In the fire history of the Daxinganling region there have been 25 extreme fires. Twenty of them occurred under this weather pattern. When the cold air mass in the Novaya Zemlya Islands moved southward, it led to the development of a warm ridge located in Lake Baykal (107°E, 53°N). Then the upper pressure pattern over Daxinganling was dominated by a powerful upper warm ridge. The warm sector of the depression occupied the potential fire area for 2-3 days before the extreme fires burst out. At surface, the center of the cyclone had intense convergence associated with high temperatures, low humidity and strong surface SW winds. Once the cold front, usually with little precipitation, moved eastward, the fire spread was subject to 'explosive' runs. Fire behavior included running, spotting, and crowning. This 1987 extreme fire was caused by this typical weather pattern (Yi Qing-ju 1988). It appears to be similar to some North American mid-high latitude fire weather patterns (Flannigan and Harrington 1986).

The Weather Elements and Components of FWI At Weather Stations

The fire weather elements from key stations, such as Amur and Mohe, were used to analyze the causes of drying fuels, strong winds and fire whirls. The weather elements of April, May and the first two days of June for Amur were also used to calculate the codes and indexes of the Canadian FWI System. The hourly fire weather readings, temperature, relative humidity, wind direction and wind speed, for Amur on May 6, 1700 hours - May 8, 0800 hours were used to calculate hourly ISI and rate of spread for larch and grass fuels in order to interpret them for the 1987 Daxinganling fire occurrence and fire behavior, as well as to determine if the Canadian system is, even partly, suitable for the north-eastern portion of China. The results are summarized in Table 3 and Table 4.

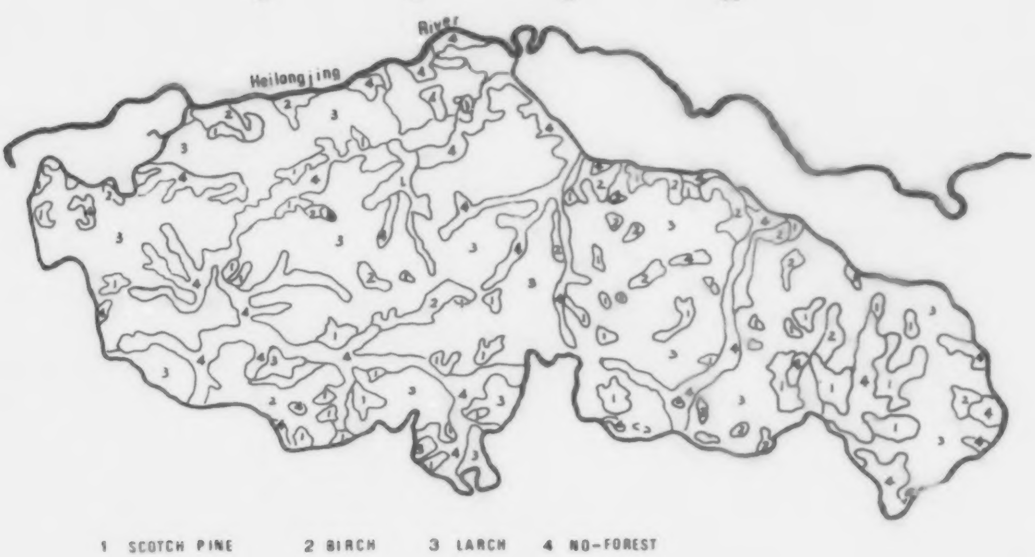

U S S R
Heilongjing River
1 SCOTCH PINE
2 BIRCH
3 LARCH
4 NO-FOREST

FIG 1. The forest type map of the fire area in Daxinanling.

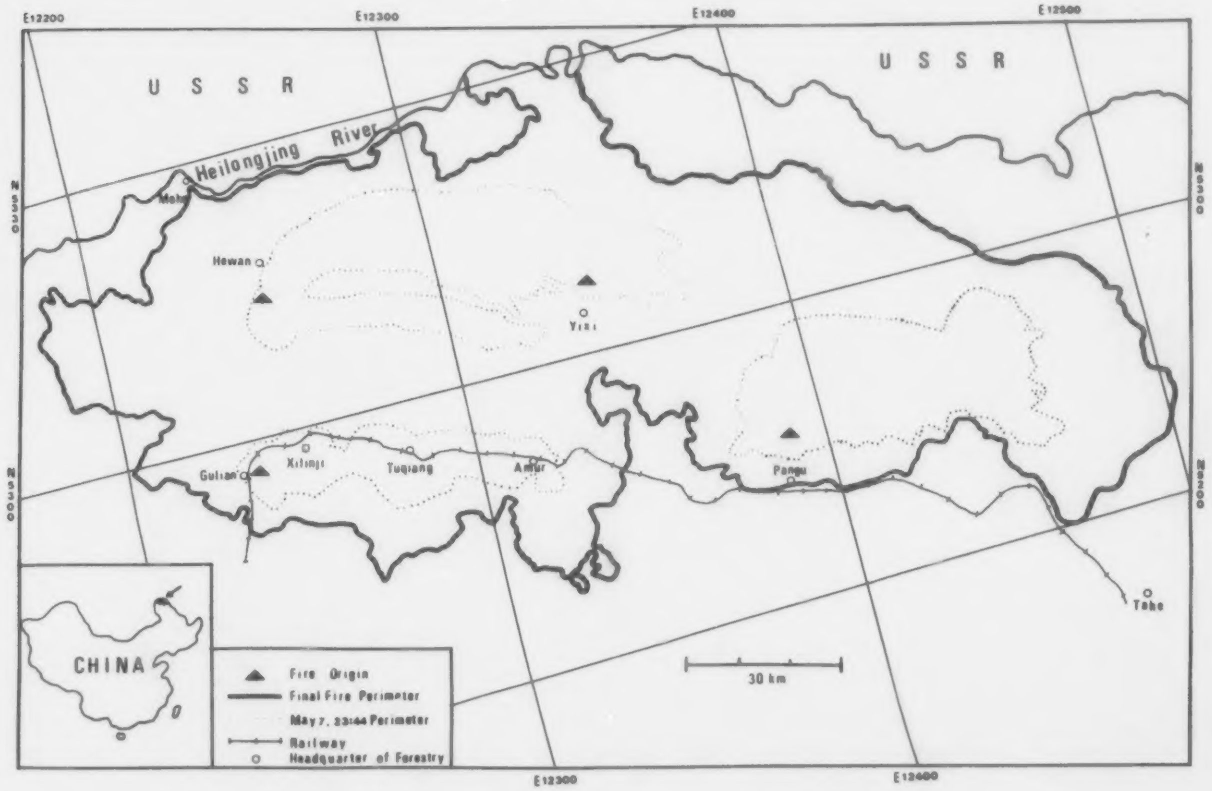
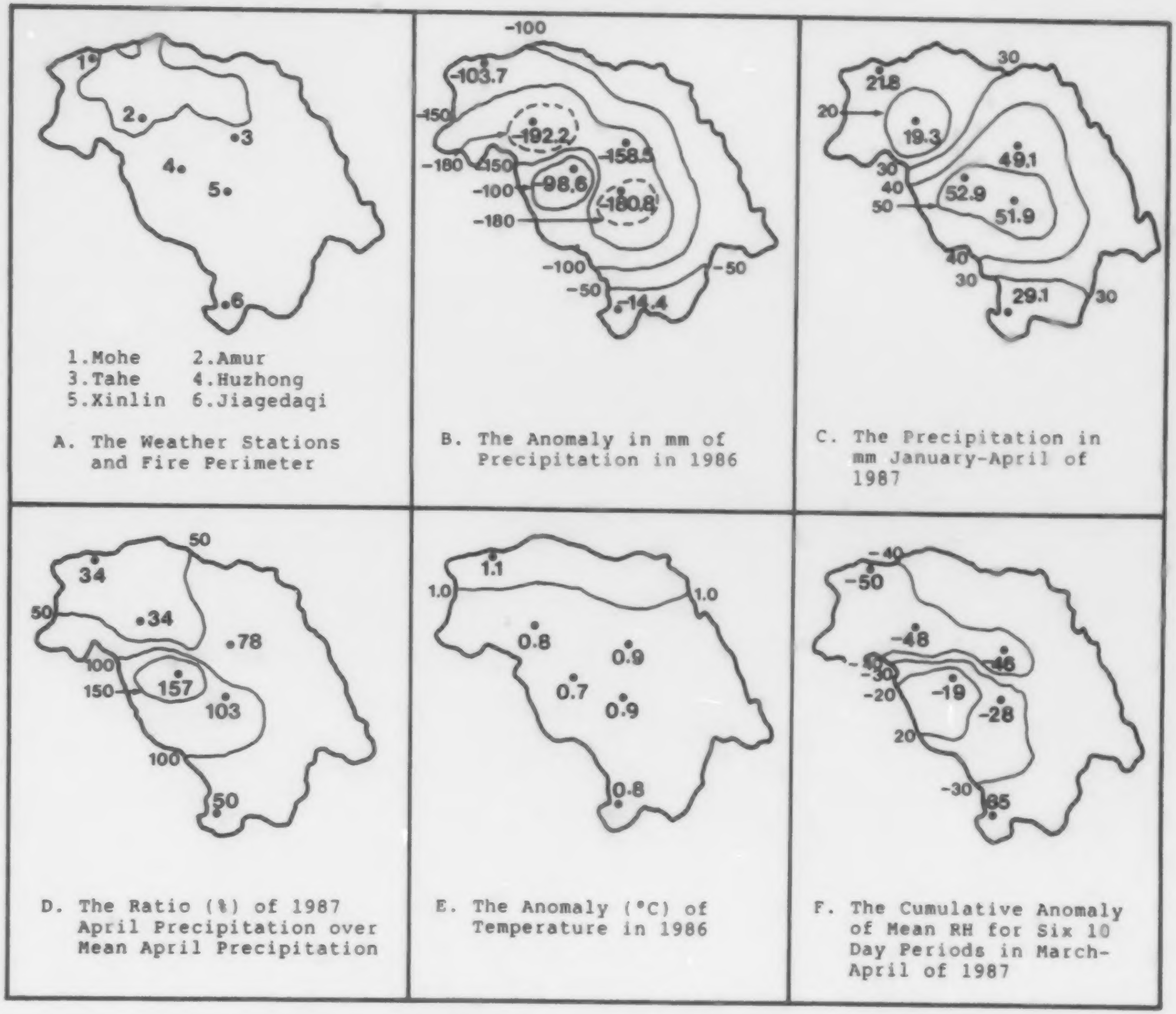

E12200
E12300
E12400
E12500
U S S R
U S S R
Heilongjing River
Mohe
Hewan
Yixi
Gulian
Xilinji
Tuqiang
Amur
Pangu
Tahe
CHINA
30 km
Fire Origin
Final Fire Perimeter
May 7, 23:44 Perimeter
Railway
Headquarter of Forestry
E12300
E12400

FIG 2. The 1987 Daxinanling final fire perimeter.


1.Mohe
2.Amur
3.Tahe
4.Huzhong
5.Xinlin
6.Jiagedaqi
1
2
3
4
5
6
-100
-103.7
-150
-192.2
-158.5
-180
150
-100
98.6
-180.8
-180
-100
-50
-50
-14.4
30
21.8
20
19.3
49.1
30
40
52.9
50
51.9
40
30
29.1
30
50
34
50
34
78
100
150
157
103
100
50
1.1
1.0
1.0
0.8
0.9
0.7
0.9
0.8
-40
-50
-48
-46
-40
-30
-20
-19
-28
20
-30
35

A. The Weather Stations and Fire Perimeter

B. The Anomaly in mm of Precipitation in 1986

C. The Precipitation in mm January-April of 1987

D. The Ratio (%) of 1987 April Precipitation over Mean April Precipitation

E. The Anomaly (°C) of Temperature in 1986

F. The Cumulative Anomaly of Mean RH for Six 10 Day Periods in March-April of 1987

FIG 3. The distributions of some climatical factors.

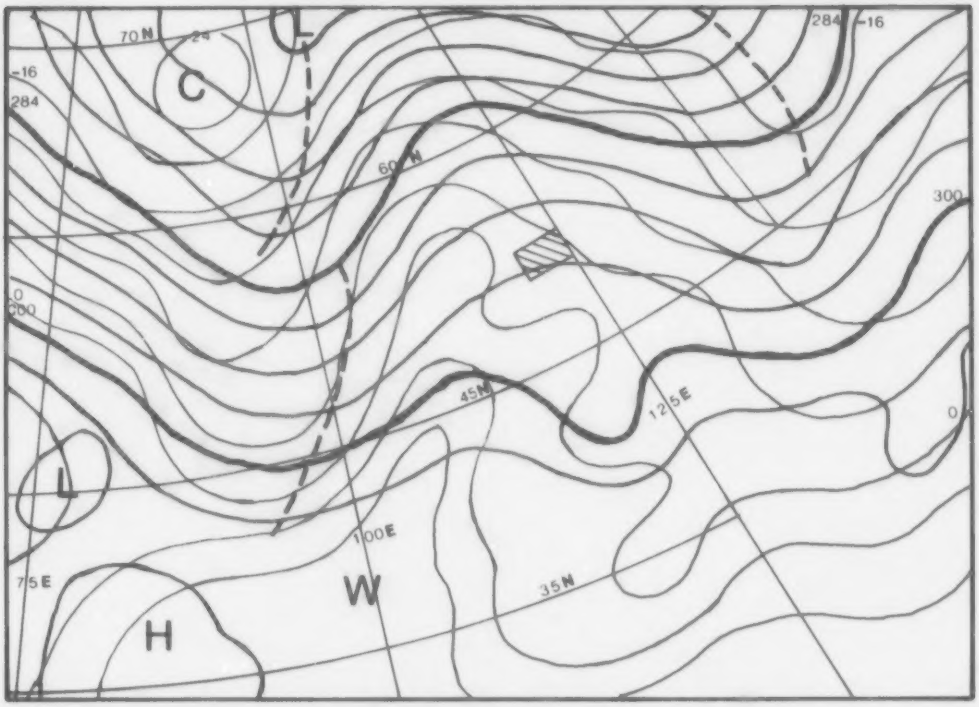

70N
-24
L
C
-16
284
284
-16
60N
300
0
300
45N
125E
0
L
100E
75E
W
35N
H

FIG 4A. The upper air chart 70 KPa of May 6, 20:00 (LST).

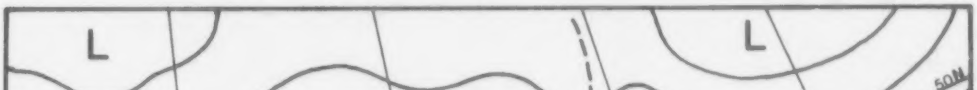

L
L
50N
1000
L
50N
140E
130E
120E
110E
10025
L
40N
1010
1000
40N
H
1010

FIG 4B. The surface chart of May 6, 14:00 (LST).

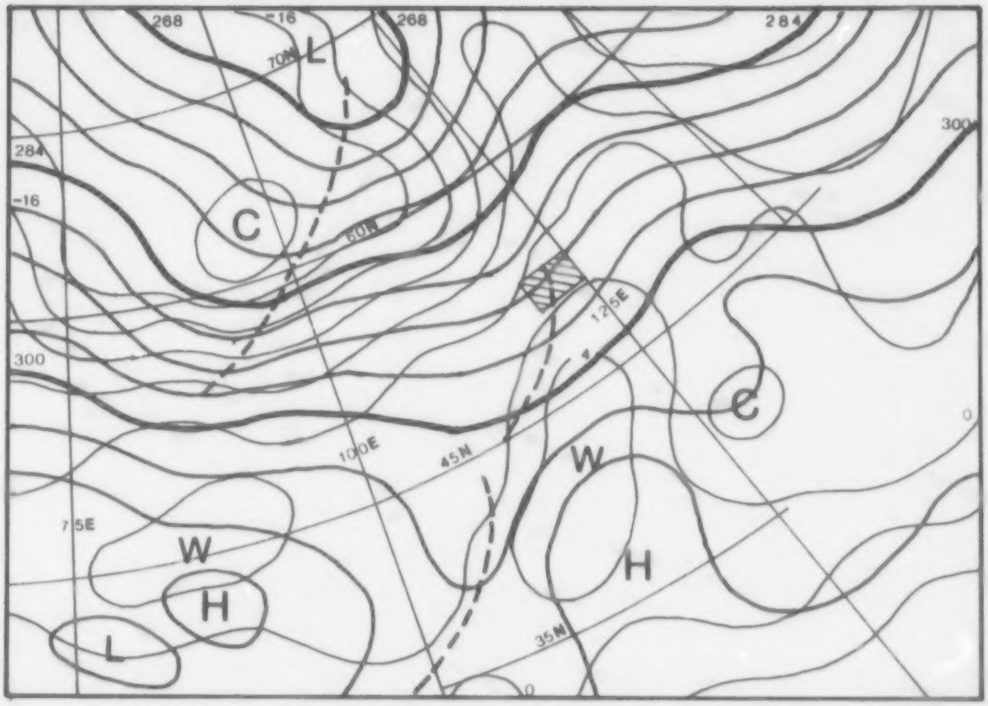

268
-16
L
268
284
70N
284
-16
C
60N
300
300
125E
C
0
100E
45N
W
75E
W
H
H
L
35N
0

FIG 5A. The upper air chart 70 KPa May 7, 20:00 (LST).

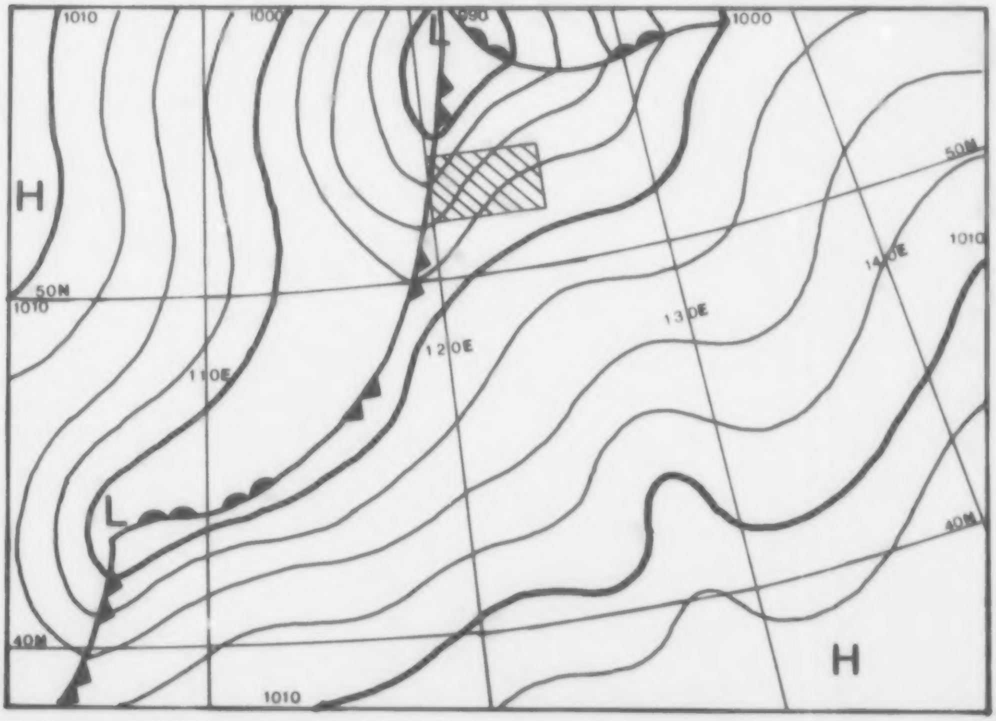

1010
1000
990
L
1000
H
50N
50N
1010
1010
140E
130E
120E
110E
L
40N
40N
1010
H

FIG 5B. The surface chart of May 7, 14:00 (LST).

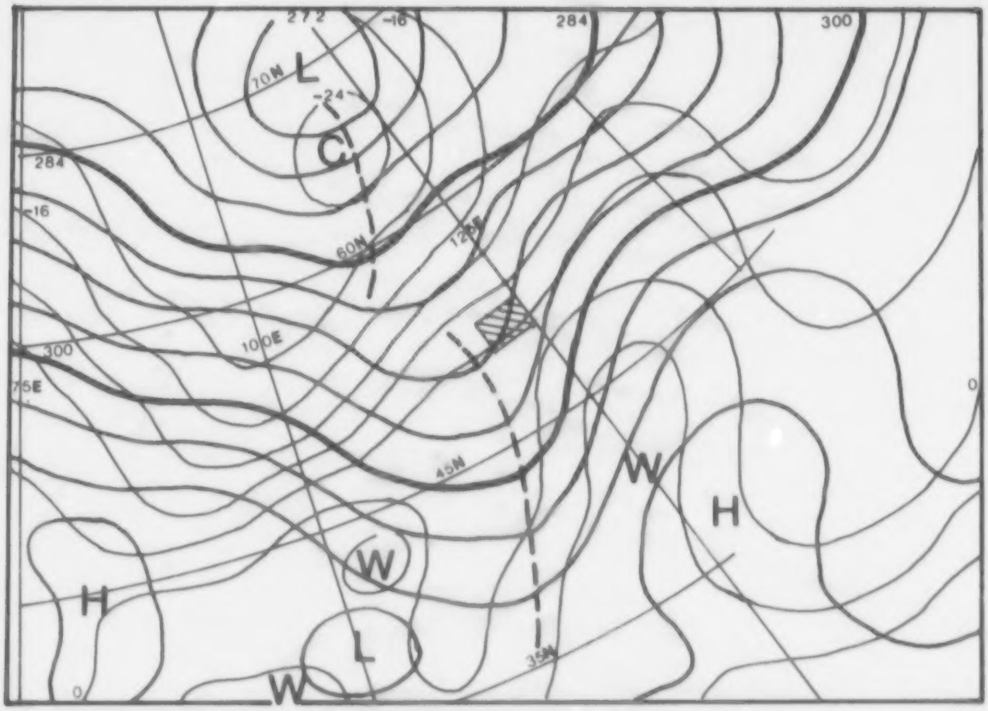

272
-16
284
300
L
70N
-24
C
284
-16
60N
120E
300
100E
75E
0
W
45N
H
W
H
L
35N
0
W

FIG 6A. The upper air chart 70 KPA of May 8, 20:00 (LST).

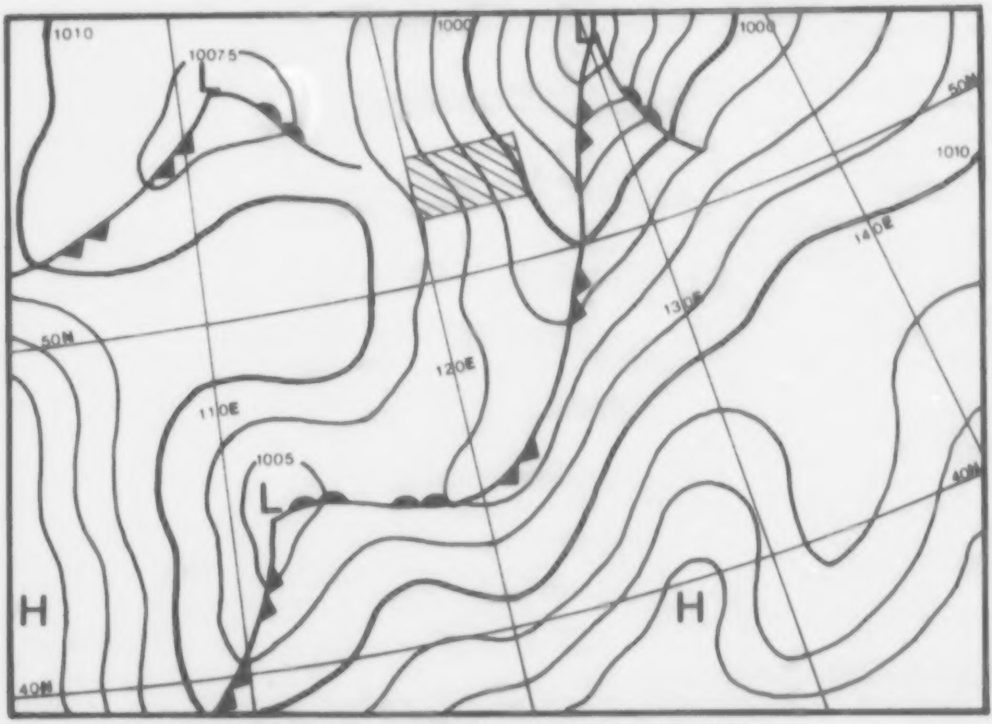

1010
10075
L
1000
L
1000
50N
1010
140E
50N
130E
120E
110E
1005
L
40N
H
H
40N

FIG 6B. The surface chart of May 8, 02:00 (LST).

Table 3. The Weather Elements and Components of Canadian FWI System from May 1 to June 2, 1987 in Amur at 11:00 LST.

1987 Month Day	T (°C)	RH (%)	WD --	WS (km/h)	RAIN (mm)	FFMC --	DMC --	DC --	IS --	BUI --	FWI --
MAY 1	3.8	27	N	18.0	0.0	88.5	24	61	8.5	24	13.7
MAY 2	2.3	28	N	16.9	0.1	88.6	25	63	8.2	25	13.5
MAY 3	2.5	17	N	25.2	0.0	90.5	26	66	16.4	26	23.0
MAY 4	10.3	31	NNE	14.4	0.0	90.6	28	70	9.6	28	16.0
MAY 5	17.1	8	NNE	22.7	0.0	95.6	32	76	29.1	31	36.8
MAY 6	21.6	4	NW	22.7	0.0	98.2	38	82	41.3	35	48.6
MAY 7*	14.2	32	S	7.2	0.0	94.1	41	87	10.9	37	20.5
MAY 8	2.0	88	NW	8.3	0.0	84.4	41	90	2.9	38	7.2
MAY 9*	4.7	29	N	14.4	2.6	70.7	35	93	1.3	36	3.0
MAY 10	6.6	9	NW	16.9	0.0	86.7	37	97	6.2	38	13.5
MAY 11	1.9	34	N	16.9	0.8	84.1	37	100	4.4	38	10.3
MAY 12*	4.8	18	N	22.7	0.0	89.2	38	103	11.9	40	22.4
MAY 13	6.5	28	N	9.7	0.0	89.3	40	106	6.3	41	14.2
MAY 14	4.8	48	SE	10.8	0.0	87.9	41	110	5.4	42	12.9
MAY 15*	8.5	17	N	1.1	0.0	90.5	43	114	4.8	44	12.0
MAY 16*	13.1	16	NNE	8.3	0.0	92.6	46	118	9.3	47	20.4
MAY 17	15.8	12	SE	8.3	0.0	94.4	50	124	12.0	50	25.2
MAY 18	11.6	43	S	14.4	0.0	90.7	52	128	9.7	51	22.0
MAY 19*	5.7	31	N	9.7	0.0	90.4	53	132	7.3	53	18.2
MAY 20*	6.9	40	NNE	7.2	0.6	87.8	54	135	4.5	54	12.7
MAY 21	16.9	8	NW	28.8	0.0	95.2	59	141	37.7	57	56.9
MAY 22	21.8	10	NNE	7.2	0.0	96.2	64	147	14.5	61	31.8
MAY 23	8.3	20	SW	10.8	0.0	94.7	66	151	14.7	63	31.8
MAY 24*	7.4	83	E	18.0	5.3	49.0	43	146	0.4	49	0.6
MAY 25*	9.3	60	N	7.2	2.5	53.3	37	150	0.3	46	0.5
MAY 26	2.7	37	WNW	13.3	0.0	70.9	37	153	1.3	46	3.5
MAY 27	14.2	41	WNW	18.0	0.0	83.4	40	158	4.2	49	11.4
MAY 28	8.5	24	N	42.1	0.2	89.0	42	162	30.7	51	47.4
MAY 29	22.4	25	WNW	25.2	0.0	92.2	46	168	20.8	55	38.3
MAY 30	28.5	15	N	11.9	0.0	95.6	53	176	17.0	60	35.1
MAY 31	29.0	23	SW	16.9	0.0	95.6	59	183	21.8	65	42.8
JUNE 1*	23.9	36	SSW	1.9	1.2	88.5	63	191	6.2	69	18.8
JUNE 2*	7.7	81	NE	3.6	6.2	40.2	39	184	0.0	51	0.1

* represents the day when the synoptic weather process was passing.

Table 4. The Rate of Spread Calculated with Canadian FWI System and FBP System for May 6, 17:00 to May 8, 08:00 of 1987 (LST) at Amur.

1987 Day	MAY TIME	T (°C)	RH (%)	WD --	WS (km/h)	RAIN (mm)	FFMC --	ISI --	ROS.C-3 (km/hr)	ROS.O-1 (km/hr)
06	17:00	13.5	10	NNW	13.3	0.0	98.1	23.9	1.7	3.6
06	18:00	11.5	11	NNW	8.3	0.0	98.0	18.2	1.0	3.0
06	19:00	9.4	13	C	0.0	0.0	98.0	11.9	0.4	2.3
06	20:00	7.4	14	C	0.0	0.0	98.0	11.8	0.4	2.3
06	21:00	5.6	18	S	1.1	0.0	97.9	12.4	0.4	2.4
06	22:00	3.8	23	S	2.5	0.0	97.7	12.9	0.5	2.4
06	23:00	2.0	27	C	0.0	0.0	97.6	11.1	0.3	2.2
06	24:00	0.1	31	SSE	7.2	0.0	97.3	15.2	0.7	2.7
07	01:00	-1.7	36	S	4.7	0.0	96.9	12.8	0.4	2.4
07	02:00	-3.5	40	SSE	9.7	0.0	96.5	15.2	0.7	2.7
07	03:00	-1.8	38	S	8.3	0.0	96.1	13.4	0.5	2.5
07	04:00	0.1	35	SSE	7.2	0.0	95.8	12.0	0.4	2.3
07	05:00	1.6	33	S	9.7	0.0	95.5	13.0	0.5	2.4
07	06:00	3.3	30	SSE	10.8	0.0	95.3	13.2	0.5	2.4
07	07:00	5.0	28	S	8.3	0.0	95.1	11.3	0.3	2.2
07	08:00	6.7	25	S	13.3	0.0	95.0	14.2	0.6	2.6
07	09:00	9.4	22	SSE	2.5	0.0	94.9	8.3	0.1	1.8
07	10:00	12.0	18	SSE	10.8	0.0	94.9	12.4	0.4	2.4
07	11:00	14.7	15	S	7.2	0.0	94.9	10.4	0.3	2.1
07	12:00	17.4	12	WSW	15.5	0.0	95.1	16.2	0.8	2.8
07	13:00	20.0	8	SWS	15.5	0.0	95.5	17.4	0.9	2.9
07	14:00	22.7	5	WSW	14.4	0.0	96.1	18.1	1.0	3.0
07	15:00	21.9	7	W	19.1	0.0	96.5	24.3	1.8	3.6
07	16:00	21.0	8	SW	9.7	0.0	96.7	15.7	0.7	2.7
07	17:00	20.2	10	SW	13.3	0.0	96.7	19.1	1.1	3.1
07	18:00	19.4	12	SSW	10.8	0.0	96.7	16.7	0.8	2.8
07	19:00	18.5	13	SW	6.1	0.0	96.7	13.2	0.5	2.4
07	20:00	17.7	15	WSW	6.1	0.0	96.7	13.1	0.5	2.4
07	21:00	16.3	20	WSW	32.4	0.0	96.5	48.3	4.4	5.5
07	22:00	14.9	25	WNW	36.0	0.0	96.2	54.9	4.8	6.0
07	23:00	13.5	30	E	28.8	0.0	95.8	35.9	3.2	4.6
07	24:00(*)	12.1	34	NNW	44.3	0.0	95.3	72.0	5.5	7.1
08	01:00	10.7	39	NW	38.5	0.0	94.8	49.2	4.5	5.6
08	02:00	9.3	44	NNW	32.4	0.0	94.3	33.1	2.9	4.4
08	03:00	9.1	45	NNW	21.6	0.0	93.8	18.0	1.0	3.0
08	04:00	8.9	47	WNW	18.0	0.0	93.4	13.9	0.5	2.5
08	05:00	8.7	48	NNW	14.4	0.0	93.0	10.9	0.3	2.2
08	06:00	8.4	49	NW	8.3	0.0	92.7	7.6	0.1	1.7
08	07:00	8.2	51	C	0.0	0.0	92.5	4.8	0.0	1.3
08	08:00	8.0	52	WNN	2.5	0.0	92.2	5.3	0.0	1.4

The FFMC were calculated with a method. (Van Wagner, C.E. 1977)
The fuel type C-3 is Mature Jack or Lodgepole Pine, here for Larch.
The fuel type 0-1 is Grass (fuel weight = 5 t/ha).
(*) If the calculation was made with the maximum wind speed of 61.2 km/h at 23:26 instead of 44.2 km/h at 24:00, the ISI, ROS.C-3, ROS.0-1 would be 167.4, 6.0 km/h, 12.0 km/h.

On May 5-7, as the temperature continued to rise, the maximum air temperature of each day was 15.6°C, 20.7°C, 23.1°C respectively; the maximum surface temperatures were 25.1°C, 34.5°C, 30.8°C; the minimum relative humidities were 20%, 5%, and record-breaking 4%. The extreme weather readings of May 4 to May 8 for Mohe and Amur are shown in Table 5. With persistent high temperatures and low humidity, the fine fuels were already extremely dry. On May 6 an extreme FFMC of 98.2 was reached. Only 0.5% of all FFMC records were in excess of 96 for Daxinganling 10 year statistics (Stocks and Lynham 1987).

Table 5. Extremes of Weather Readings

1987		Max. T (°C)		Min. R H (%)		Max. Surface T (°C)	
Month	Day	Mohe	Amur	Mohe	Amur	Mohe	Amur
MAY	4	7.8	6.4	21	9	27.0	23.7
MAY	5	17.7	15.6	19	20	29.8	25.1
MAY	6	21.9	20.7	21	5	41.4	34.5
MAY	7	23.9	23.1	4	4	31.0	30.8
MAY	8	19.7	18.8	16	16	36.2	29.0

Figure 7 shows Mohe, Amur, Tahe, Huma stations hourly wind speed and wind direction on May 7 evening to May 8 morning from autographic records. The cold front passed above the 4 stations at 1900 hours, 2100 hours, 2200 hours and 0300 hours respectively. Associated were 29 km/h - 43 km/h wind speeds from W - NW. For 2 hours following the cold front passage a gust of backing cold air additionally strengthened the wind speed. The maximum wind speed recorded was 50.4 km/h from W at 2134 hours for Mohe, 61.2 km/h from NNW at 2326 hours for Amur. There was evidence of a wind shift to the east at Amur by 23:00 to imply that a small-scale cyclone convergence had occurred over the fire area (Figure 7). It triggered large fire convective column development and fire whirls. In only a few hours the fire advanced over 100 km (Figure 2). The wind field played a major role in the rapid expansion of the fire perimeter.

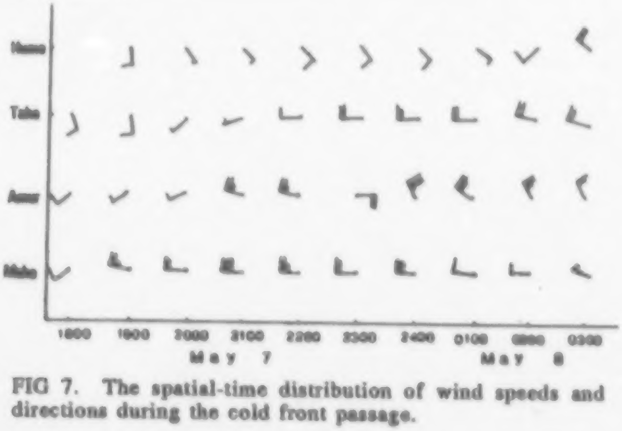


FIG 7. The spatial-time distribution of wind speeds and directions during the cold front passage.

As the cold front passed at Amur by 2100 hours of May 7, the wind direction changed from SW to WNW or NNW. The wind speed rose from 6.1 km/h (2000 hours) to a maximum 61.2 km/hr (2326 hours). The ISI and ROS for C-3 fuel (Larch-equivalent) and 0-1 fuel (Grass) were increased from 13.1, 0.5 km/h (C-3), 2.4 km/h (0-1) to maximum 167.4, 6.0 km/h (C-3), 12.0 km/h (0-1). According to an investigation (Li Zhi-fang 1988), the estimated ROS was 11.3 km/h from Xilinji to Amur in the evening of May 7 (the fire took 4.1 hours to go over the 46 km between Xilinji and Amur). The fire spread eastward along the river valley in which there was much grass and secondary forest. Meanwhile the fire perimeter expanded on the flank in the Larch fuel. Explosive spread lasted for 5-6 hours. After 0300 hours of May 8 the ISI and ROS rapidly decreased as the cold front passed.

The Weather Pattern for the Fire Persistence

Persistent drought over the previous two years was one of the underlying causes of the prolonged fire event, making it difficult to extinguish; however, the weather patterns during the fire period also contributed to the persistence of the fire.

After the first synoptic scale system, there were five more that passed the fire area. The date of passages were on May 9, 12, 15, 20, 25. These systems had the following common circulation characteristics: the upper frontal zone was oriented in a west-eastern direction, the meridional index was low, the troughs and ridges moved fast. The corresponding surface weather characteristics included many shifts of wind direction and no appreciable precipitation (except May 25), as well as low humidity. The fuel moisture content had still been retained under the critical situation. Most of the FFMC values had been kept above 87, with the FWI above 12. Fire fighters had a difficult time to suppress the fire with so much dry fuel. On May 24-25 most fires were put out mainly due to extensive rainfall. There was a total of 7.8 mm rain at Amur. The FFMC, ISI, FWI dropped to 53.3, 0.3, 0.5. The remaining smouldering fires burned again over the next 5 days because the FFMC, ISI, FWI climbed to 95.6, 21.8, 42.8 on May 31st. As a weather system brought appreciable rain, 7.4 mm, 1-2 June at Amur, the FFMC, ISI, FWI dropped down to 40.2, 0.0, 0.1. The fire was eventually extinguished on June 2.

Discussion

1. The extreme China fire in 1987 occurred against a background of prolonged drought. Previously, a great fire in the northern part of Daxinganling before the middle of May was not believed possible. We may need a study of the effect of prolonged drought on the moisture content of fuels such as crown foliage and medium-sized woody material. The indicators of over-winter drought effects on these forest fuels will be

used to make a long-term prediction of the fire severity for the coming fire season.

2. The local wind field was affected not only by surface and upper air patterns, but also by thermal convection. We strongly suspect that there was a coupling of the low level jet stream with the fire thermal convection resulting in strong surface winds and strengthening of horizontal shear of wind on May 7. Unfortunately, there is not an upper air sounding station in the the Daxinganling region. But some upper wind readings from a nearby sounding station imply that a vertical wind shear might have existed (Table 6).

The super-intense fire would be able to create a local small-size circulation pattern resulting in surface convergence and upper divergence. With the upper divergence the sinking flow created a great amount of descending air, reinforcing the surface wind and creating a shear of wind direction on the ground.

Table 6. The Vertical Wind Profile (Near Mohe) on May 7 at 20:00 LST.

Surface(*)	85 kPa	70 kPa	50 kPa
25.2 km/h	57.6 km/h	72.0 km/h	79.2 km/hr

(*) The surface wind speeds were taken at Mohe.

Therefore it might be supposed that if there was no fire the wind would not be so strong. Secondly, the convergence of frontal action would conversely prompt the thermal convection causing fire whirls. In spite of the difficulty, a study of the lower layer jet stream prediction will probably be one of the keys to predict a potential extreme fire.

3. The Canadian Fire Weather Index System and part of the Fire Behavior Prediction System have been used in Daxinganling for four years (Jin Ji-zhong 1986, Stocks and Lynham 1987, Jim Ji-zhong 1988). The FWI system and FBP system fit well with the Daxinganling region situation even in prediction of extreme fire behaviour. But more time should be spent gaining experience with these systems and interpreting the system components. Calibration and adjustments to some components of the systems should be done to complete implementation in north-eastern China.

4. It would be desirable to develop a set of indexes as a quantitative relationship between upper air patterns and FWI system components over a 2-3 day forecast period in order to improve mid-term prediction of the fire situation.

References

CHINA STATE COUNCIL EXPERTS GROUP. 1988. The Reports Assembly of Investigation on Forest Resources Recovery and Fire Ecological Environment in 1987 Daxinganling Extreme Fire Area. China Forestry Press, 1988.

DAI CHANG-DA. 1988. The Theory and Efficiency for Forest Fire Analysis Using TM Images of Landsat. Developments of Remote Sensing Technology, 1988, No. 3.

FLANNIGAN, M.D., AND B.J. HARRINGTON. 1986. Synoptic Weather Conditions During the Porter Lake Experimental Fire Project. Climatological Bulletin 20 (2) 1986.

HEILONGJIANG PROVINCE WEATHER ADMINISTRATION. 1987. On the Extreme Forest Fire of May 6, 1987. Unnumbered Publ.

JIN K.C., AND XIAO G.W. 1984. The Survey of Forest Fuel Geographic Distribution in the Daxinganling Region. Forest Fire Control, 1984, No. 1-2.

JIN JI-ZONG. 1986. The Primary Implementation of the Canadian FWI System in the Daxinganling Region. Forest Fire Control, 1986, No. 3.

JIN JI-ZHONG. 1988. The Fire Behavior Computation, A Project Review Report. Heilongjiang Forest Protection Research Ins., Dec., 1988. Unnumbered Publ.

JIN XIAO-ZHONG. 1988. The Atmospheric Environment of the 1987 Daxinganling Extreme Fire. Heilongjiang Forest Protection Research Ins. Unnumbered Publ.

LI ZHI-FANG. 1988. A Study on Making Decisions on Suppression During the 1987 Daxinganling Extreme Fire. Heilongjiang Forest Protection Research Ins. Unnumbered Publ.

LOU YUHAI AND WANG SOUXIN. 1988. Analysis on Forest Fires in the Great Xingan Forest Region. Journal of Ecology, Vol. 7 (sup.), 1988. pp. 30-34.

STOCKS, B.J., AND T.J. LYNHAM. 1987a. Suitability of the Canadian Forest Fire Danger Rating System for Use in the Daxinganling Forestry Management Bureau, Heilongjiang Province, China. Great Lakes Forestry Center, Can. For. Serv., Unnumbered publ.

STOCKS, B.J., M.E. ALEXANDER, B.D. LAWSON, AND C.E. VAN WAGNER. 1987b. Canadian Forest Fire Danger Rating System - Users' Guide. The Canadian Forestry Service Fire Danger Group.

VAN WAGNER, C.E. 1977. A Method of Computing Fine Fuel Moisture Content Throughout the Diurnal Cycle. Can. For. Serv. Inf. Rep. PS-X-69.

WANG ZHENGFEI. 1988. Outbreak, Development and Extinction of the Super-intensive Forest Fire in the North Great Xingan Mountains and Its Future Counter-measures. Journal of Ecology, Vol. 7 (sup.) 1988, p. 26-29.

YI QING-JU. 1988. The Cause of Formation of Heavy Forest Fires in the Daxingan Mountains in May 1987. Meteorological Monthly. Vol. 14. No. pp. 31-34.

ZHAO DACHANG. 1988. Vegetation and their Restoration After the Disastrous Fire in the Great Xingan Mountains. Journal of Ecology, Vol. 7 (sup.), 1988, p. 35-40.

Use of Numerical Weather Prediction Models for Medium/Extended-Range Fire Weather Forecasting

K. UEYOSHI AND J.O. ROADS
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, California

Abstract

A proposed plan for assessing the skill of present-day weather forecast models to forecast fire weather is described. The first component will be concerned with describing climatological and temporal variations in the Fosberg fire weather index from the NMC global objective analysis of temperature, relative humidity, and wind speed at 1000 mb level and at the surface using station data. The second component will be to assess the skill of present-day numerical weather prediction models in predicting this fire weather index. At the end of this research, we hope to develop an 11-year data set of meteorological variables applicable to fire weather forecasting on the regional as well as national scale.

Résumé

Un plan est proposé évaluant l'habilité des modèles de prévisions météorologiques d'aujour d'nui à prévoir la forêt-météo est décrit. La première compisante décrit les variations de la température et de la climatologie de l'indice Fosberg forêt-météo provenant de l'analyse objective globale de la température, de l'humidité relative et de la vitesse du vent à la surface et à 1000 mb de hauteur.

La deuxième composante vu évaluer l'habilité des modèles numériques de prévisions météorologiques d'aujourd nui à prévoir cit indice forêt-météo. À la fin de cette recherche, on espère pouvoir développer une sériè de 11 ans de données de variables météorologiques qui s'appliqueraient aux prévisions forêt-météo sur une base régionale ainsi que nationale.

Introduction

In a recent article Fosberg and Fujioka (1987) described the potential importance of accurate national weather forecasts for developing appropriate responses to wildfires. As part of this effort, the goal of the proposed work to be described is to assess the capability of present operational numerical weather prediction models to forecast fire potential on a U.S.-wide scale.

Our initial efforts have been devoted to acquiring and developing the necessary observational and forecast data to describe the Fosberg fire weather index (FWI). This index was first described by Fosberg (1978) as a simplified version of the burning index (Deeming et al. 1977), which expresses a measure of the difficulty of containing a fire. The major simplification of the FWI is the assumption of uniform fuel characteristics. However, a previous study (Haines et al. 1983) has shown that it is especially valuable for forecasting fire occurrence in the northeastern region of the U.S. If more elaborate indices are necessary in order to describe fire occurrence on a nation-wide scale, then the meteorological data acquired here can be put to further use. In essence, we feel this simplification is necessary in order to concentrate our efforts in acquiring and developing the necessary large scale meteorological data applicable to large scale fire weather forecasting.

The FWI is computed from the following expression given in Fujioka and Tsou (1985):

$$FWI = (1 + U^2)^{1/2}(1 - 2a + 1.5a^2 - 0.5a^3)/0.3002, \qquad (1)$$

where U is the wind speed in the units of statute mph and the parameter "a" is the ratio of equilibrium moisture content to a moisture of extinction of 30%. The equilibrium moisture content is determined from dry-bulb temperature, and relative humidity, RH (see Simard 1968). We ignore the explicit effects of precipitation on the parameter "a" at this stage of our project development.

Figure 1 shows the parameter dependence of the FWI on temperature, RH and U. The higher values of the FWI are supposed to represent a greater potential for

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

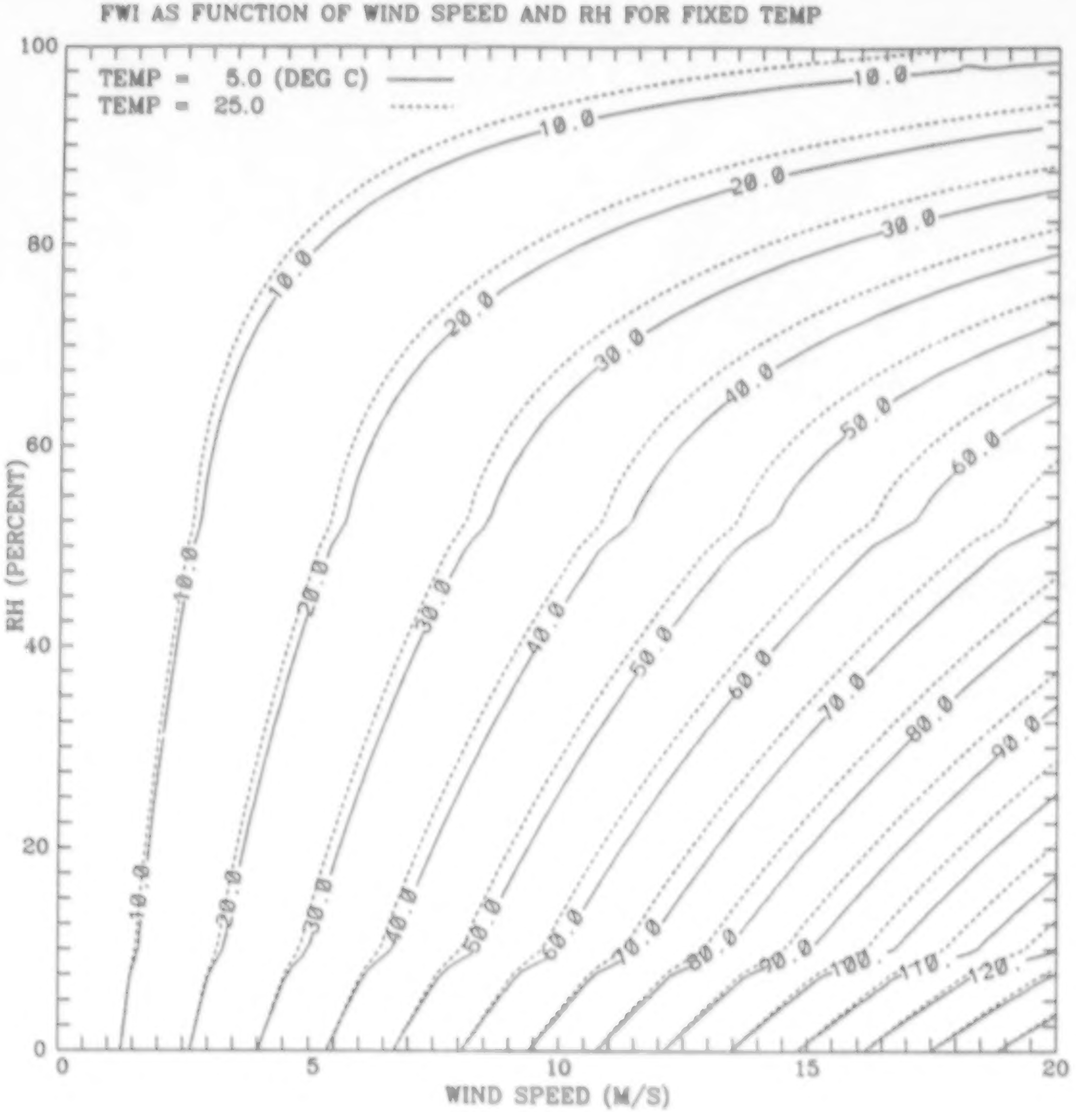


FIG 1. The FWI as a function of wind speed (abscissa) and relative humidity (ordinate) for temperatures of 5 (solid) and 25 (dashed) °C.

fire activity. As may be seen, the temperature dependence is almost negligible. For increased temperature the FWI increases only slightly. Much stronger variations occur due to RH and U. As might be expected the FWI increases for increased U and decreased RH. In the following sections, we describe in detail how we intend to evaluate this index.

We intend to carry out three efforts. The first effort will be involved with evaluating this index from the global National Meteorological Center (NMC) objective analysis. This analysis is available for over eleven years on a 2.5°x2.5° grid. The second effort will compare the observed index with a forecast index calculated over a short span of 30-day forecasts. The third effort will compare the index calculated from the NMC objective analysis grid to that calculated from individual stations. After this three-stage effort, we should have an idea about how accurate this index can be forecast with modern numerical weather prediction models and how representative these forecasts on a large-scale grid are to station observations.

Analysis of the FWI From the NMC Objective Analysis

We have begun to evaluate the significance and predictability of the FWI as a measure of fire occurrence on a nationwide scale. In particular, we have computed the FWI in the lower 48 States and Alaska for the period beginning 1 July 1976 and ending 31 December 1987. This evaluation has been carried out using the NMC objectively-analyzed 1000 mb temperature, relative humidity and wind speed available from National Center for Atmospheric Research (NCAR). The NMC data is available on a 2.5°x2.5° grid mesh (approximately 280 km x 200 km at 45°N).

Figure 2 shows the annual means of basic meteorological variables and the FWI, and Figure 3 gives the annual standard deviations. The FWI shows a strong to moderate dependence on wind speed and RH variations and is only weakly dependent upon temperature. It should be stressed here that the FWI was calculated from daily values and then averaged. This procedure provides a more accurate depiction of the average than simply using monthly averaged meteorological data to calculate the FWI.

There are several problems with the analysis as it now stands. The principal defect is that the meteorological data is extrapolated to 1000 mb. We intend to address this issue below by comparing station values to the 1000 mb analysis. We are especially interested in determining if the anomalous values derived for the 1000 mb grid are highly correlated with the anomalous station values. We also attempt to utilize the 850 mb NMC objective analysis from NCAR to see if extrapolations of the basic variables to an assumed surface might provide an even better large-scale description.

However, in a preliminary attempt to evaluate the monthly variations of the FWI, we have decided to calculate a standardized FWI. That is, the overall mean is subtracted from each monthly grid-point average and the resulting anomaly is then divided by the overall standard deviation appropriate to each grid point. This provides an approximately normalized variation of the seasonal change in the FWI across the country. Of course it does not represent the absolute value of the fire potential but it is our feeling that the FWI may be inadequate for that purpose anyway.

The standardized monthly departures of the FWI are shown in Figure 4. As may be discerned, a clear dichotomy exists between the western and eastern parts of the coterminous U.S. During the summer the FWI is high in the West and low in the East. A reversal occurs during the winter. While this variation must certainly contribute to seasonal fire activity it is clear that this index may have a problem in adequately representing fire occurrence. A chief problem appears to be the lack of precipitation history. For example, if this precipitation accumulation or deficit were properly accounted for then presumably in California the maximum in a more accurate index would shift toward the fall season. Other parts of the country may show less of a temporal shift.

Still, the FWI may represent an appropriate index to calculate deviations from long term trends and may be the appropriate variable to attempt to predict from medium-range weather forecasts. As such we intend to further pursue the analysis of the FWI by analyzing archived extended-range forecast data. In essence we intend to determine how far in advance the FWI can be accurately forecast.

Analysis of Extended-Range Forecasts

A reduced version of the second phase NMC Dynamical Extended-range Forecast (DERF) II data, which we intend to utilize for our present study, consists of 108 consecutive (starting 00UTC each day) 30-day forecasts beginning 14 December 1986. These predictions were done with a research version of the NMC operational medium-range forecast model. The fields in the above version of the DERF data set were produced by reducing the global mandatory upper pressure level data in the form of spherical harmonics coefficients at a resolution of rhomboidal 30 (R30) to triangular 20 (T20). These fields include u and v components of the winds, temperature, and relative humidity at 1000 and 850 mb. Reduced global surface data in DERF II, on the other hand, is provided on a 4° latitude by 5° longitude grid (72 x 46) mesh by area-averaging the original surface data available on a 102 (north-south) x 128 (east-west) gaussian grid.

After extracting the values of appropriate meteorological elements and extrapolating/interpolating to proper height levels, Eq. (1) will be utilized for calculation of the FWI for each 4° x 5° rectangular domain surrounding a grid point. The horizontal distributions of the FWI over the coterminous U.S. and Alaska will be plotted for selected ranges of forecasts, e.g., 5, 10, 15, 20, and 30 day, and comparisons will be made with the corresponding distributions of the FWI based on the NMC objective analysis. We will initially use standard measures of comparison such as RMS error and pattern correlation, but we are concerned that the FWI may be decidedly non-normal (Fujioka and Tsou 1985). The sample distribution of fire weather index shown in Figure 5 has been obtained by counting all the FWI values from the above-mentioned NMC objective analysis at the grid points within the coterminous U.S. and Alaska (over 1.4 million values). It exhibits the asymmetric nature of the FWI distribution, with the data being skewed to the right and the mean value exceeding the median. We may therefore have to develop a comparison that takes into account explicitly the distribution of the FWI.

As part of future efforts, ongoing archives of medium-range predictions (1-10 days) have been requested from NMC's Climate Analysis Center. Apparently the only near-surface prediction data currently available is 850 mb data and thus another part of the work must be involved with evaluating the relationship of this level to the 1000 mb level and to the surface observations. If these initial evaluations prove useful then it should be possible to develop an operational procedure based on numerical weather prediction that could be used by fire weather forecasters.

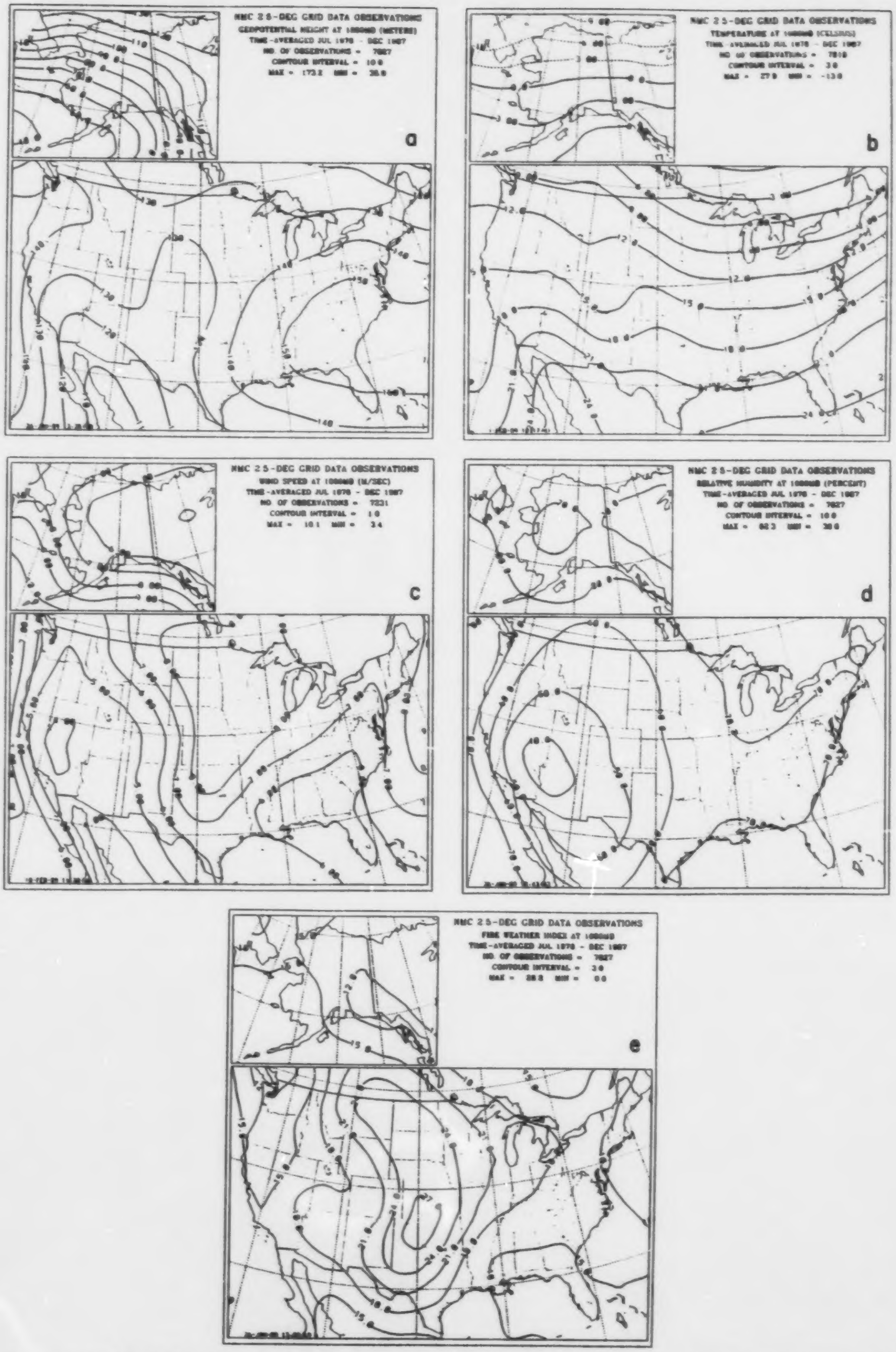

NMC 2.5-DEG GRID DATA OBSERVATIONS
GEOPOTENTIAL HEIGHT AT 1000MB (METERS)
TIME-AVERAGED JUL 1978 - DEC 1987
NO. OF OBSERVATIONS = 7027
CONTOUR INTERVAL = 10.0
MAX = 173.2 MIN = 30.0
a
NMC 2.5-DEG GRID DATA OBSERVATIONS
TEMPERATURE AT 1000MB (CELSIUS)
TIME-AVERAGED JUL 1978 - DEC 1987
NO. OF OBSERVATIONS = 7018
CONTOUR INTERVAL = 3.0
MAX = 27.9 MIN = -13.0
b
NMC 2.5-DEG GRID DATA OBSERVATIONS
WIND SPEED AT 1000MB (M/SEC)
TIME-AVERAGED JUL 1978 - DEC 1987
NO. OF OBSERVATIONS = 7231
CONTOUR INTERVAL = 1.0
MAX = 10.1 MIN = 3.4
c
NMC 2.5-DEG GRID DATA OBSERVATIONS
RELATIVE HUMIDITY AT 1000MB (PERCENT)
TIME-AVERAGED JUL 1978 - DEC 1987
NO. OF OBSERVATIONS = 7027
CONTOUR INTERVAL = 10.0
MAX = 82.3 MIN = 30.0
d
NMC 2.5-DEG GRID DATA OBSERVATIONS
FIRE WEATHER INDEX AT 1000MB
TIME-AVERAGED JUL 1978 - DEC 1987
NO. OF OBSERVATIONS = 7027
CONTOUR INTERVAL = 3.0
MAX = 38.8 MIN = 0.0
e

FIG 2. Annual averages of the basic meteorological variables and the FWI for the domain used for the study: (a) geopotential height; (b) temperature; (c) wind speed; (d) relative humidity; and (e) FWI.

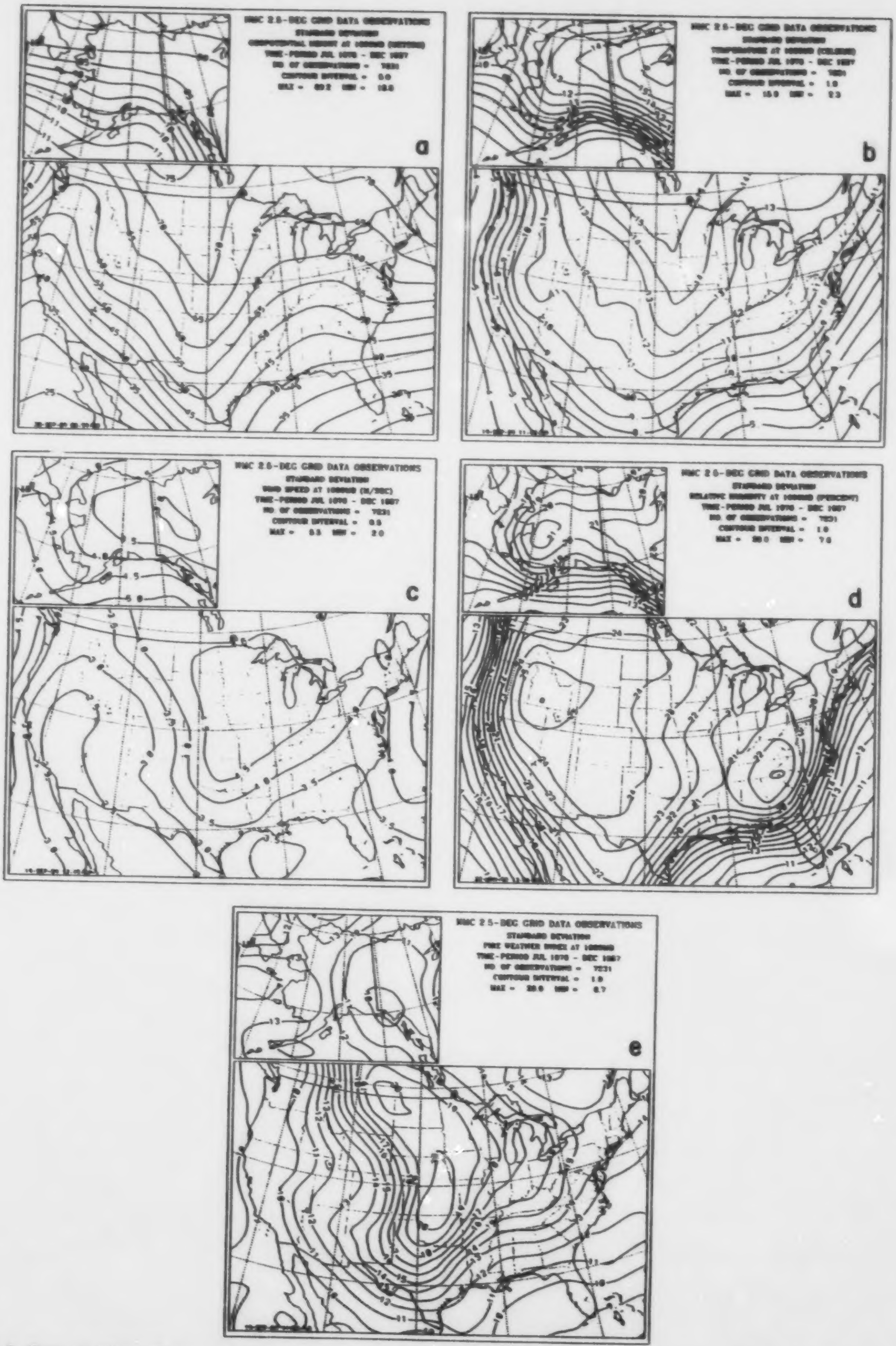


FIG 3. Same as Figure 2 except for the annual standard deviations of the basic meteorological variables and the FWI.

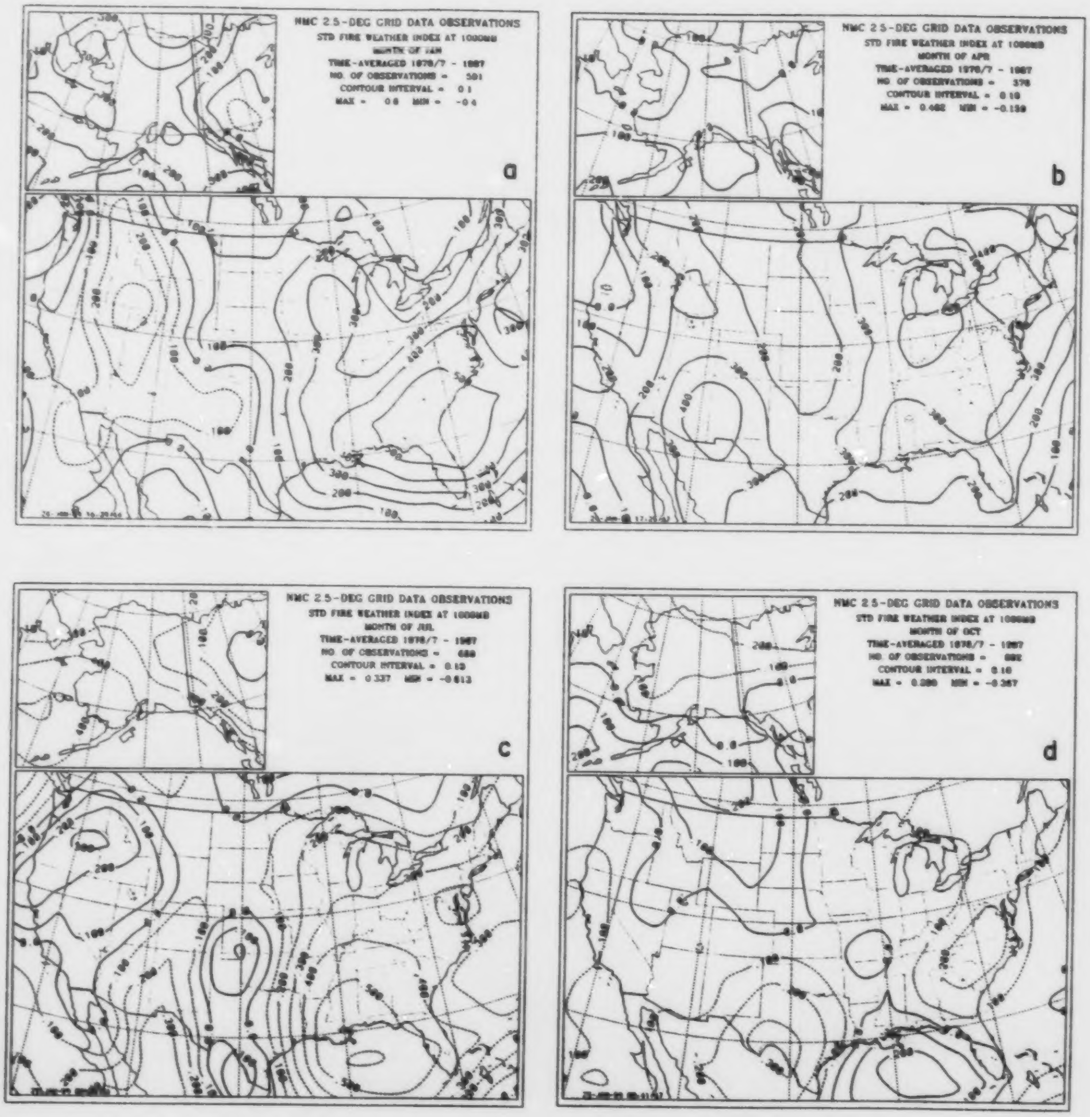

NMC 2.5-DEG GRID DATA OBSERVATIONS
STD FIRE WEATHER INDEX AT 1000MB
MONTH OF JAN
TIME-AVERAGED 1978/7 - 1987
NO. OF OBSERVATIONS = 361
CONTOUR INTERVAL = 0.1
MAX = 0.6 MIN = -0.4
a
NMC 2.5-DEG GRID DATA OBSERVATIONS
STD FIRE WEATHER INDEX AT 1000MB
MONTH OF APR
TIME-AVERAGED 1978/7 - 1987
NO. OF OBSERVATIONS = 378
CONTOUR INTERVAL = 0.10
MAX = 0.482 MIN = -0.139
b
NMC 2.5-DEG GRID DATA OBSERVATIONS
STD FIRE WEATHER INDEX AT 1000MB
MONTH OF JUL
TIME-AVERAGED 1978/7 - 1987
NO. OF OBSERVATIONS = 688
CONTOUR INTERVAL = 0.10
MAX = 0.337 MIN = -0.613
c
NMC 2.5-DEG GRID DATA OBSERVATIONS
STD FIRE WEATHER INDEX AT 1000MB
MONTH OF OCT
TIME-AVERAGED 1978/7 - 1987
NO. OF OBSERVATIONS = 992
CONTOUR INTERVAL = 0.10
MAX = 0.280 MIN = -0.267
d

FIG 4. Monthly variations of the standardized FWI: (a) January, (b) April, (c) July, and (d) October.

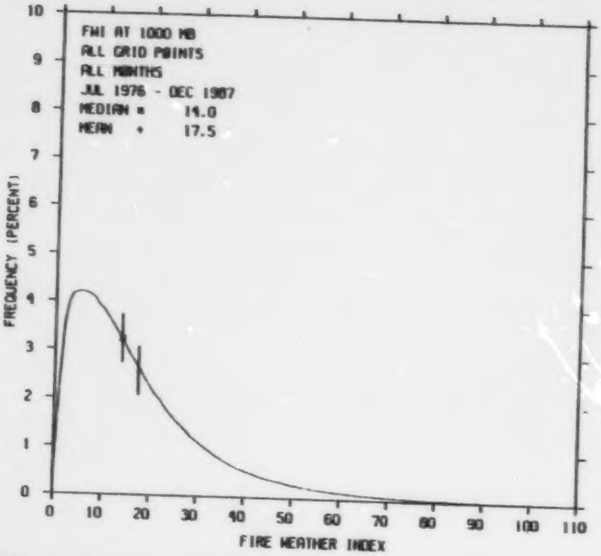


FIG 5. Sample distribution of fire weather index. The distribution was obtained by counting all the FWI values at 1000 mb from the NMC objective analysis at the grid points within the coterminous U.S. and Alaska.

Summary

A proposed plan for using objectively analyzed NMC analyses and forecasts as well as local observations to describe and forecast the Fire Weather Index has been described. We have begun to carry out the analysis of the appropriate meteorological variables to describe the FWI. This data set will be made available to any interested parties.

Both the most difficult and the most time-consuming part of our initial effort in the implementation of medium- and extended-range forecasts in fire management planning in general and the prediction of the FWI in particular is, as Gilman (1985) put it, finding the data, acquiring it, and then extracting the appropriate data set to be utilized for our ultimate objectives. With the data sets we have so far acquired or are in the process of getting possession, we are now concentrating our efforts on extracting appropriate data necessary to calculate the FWI and to build up the data base needed for extended-range fire weather severity forecasting.

What has not yet been done is to determine if the FWI is the appropriate national index to adequately predict fire weather. This will need to eventually be assessed with various measures of fire activity. However, with the data sets that we have developed and are acquiring, it should be possible to construct additional indices if this is deemed to be necessary.

References

DEEMING, J.E., R.E. BURGAN, and J.D. COHEN, 1977: The national fire danger rating system-1978. USDA For. Serv. Gen. Tech. Rep., INT-39, 63 pp.

FOSBERG, M.A., 1978: Weather in wildland fire management: the fire weather index. Proc. of the Conference on Sierra Nevada Meteorology, South Lake Tahoe, 1-4.

FOSBERG, M.A. and F.M. FUJIOKA, 1987: Medium- and extended-range fire severity forecasting: A national research plan. In Preprints Ninth Conference on Fire and Forest Meteorology, San Diego, Amer. Meteor. Soc., 273-277.

FUJIOKA, F.M. and T.H. TSOU, 1985: Probability modeling of a fire weather index. In Preprints Eighth Conference on Fire and Forest Meteorology, Detroit, Soc. Amer. Foresters, 239-243.

[illegible]MAN, D.L., 1985: Long-range forecasting: The present [illegible] the future. Bull. Amer. Met. Soc., 66, 159-164.

[illegible]NES, D.A., W.A. MAIN, J.S. FROST and A.J. SIMARD, 1983: Fire-danger rating and wildfire occurrence in the northeastern United States. For. Sci., 66, 159-164.

SIMARD, A.J., 1968: The moisture content of forest fuels I. A review of the basic concepts. For. Fire Res. Inst., Ottawa, Ontario. Inf. Rep., FF-X-14, 46 pp.

Spatial Interpolation of Fire Potential Forecasts in Complex Terrain of California

M. H. MCCUTCHAN
Pacific Southwest Forest and Range Experiment Station
Forest Service, U.S. Department of Agriculture
Riverside, California

T. H. TSOU
Department of Statistics, University of California
Riverside, California

Abstract

Regression models for interpolating 30-day fire potential forecasts in complex terrain in California are being developed. The fire potential is forecast from "perfect prog" forecasts of monthly mean temperature, dewpoint, and windspeed at 1300 PST, and monthly mean precipitation amount and precipitation frequency at National Weather Service (NWS) stations. The forecasts are used to calculate those weather-driven indices best correlated with measures of fire severity on nearby National Forests. The models being developed will spatially interpolate or extrapolate fire potential forecasts from the NWS stations to fire weather stations located in mountainous terrain, providing more detailed analysis of the regional variations of the fire potential forecasts.

Résumé

Des modèles de régression sont actuellement élaborés pour interpoler les prévisions des dangers de feu de 30 jours en terrain complexe en Californie. Les prévisions des dangers de feu sont établies à partir de prévisions de "prog parfaites" de la température moyenne mensuelle du point de rosée et de la vitesse du vent de 13 h, heure normale du Pacifique, et de la hauteur et de la fréquence moyennes mensuelles des précipitations enregistrées aux stations du National Weather Service (NWS). Les prévisions servent de données d'entrée pour calculer les indices météorologiques les mieux corrélés aux mesures de la sévérité du feu dans les forêts nationales environnantes. Les modèles qui sont actuellement élaborés permettront l'interpolation ou l'extrapolation spatiale des prévisions des dangers de feu des stations du NWS aux stations forestières météo-incendie situées en terrain montagneux permettra d'analyser de façon plus détaillée les variations régionales des prévisions des dangers de feu.

Introduction

Fire management in the United States is being shaped by forces well outside individual fire organizations. As the task of fire protection becomes increasingly expensive and complex, the business of fire protection must evolve in kind. The need to share fire suppression resources nationally requires planning on a 15- to 30-day horizon (Deeming 1987). A few years ago, any planning beyond 5 days would have been frustrated by the lack of weather predictions--a critical ingredient in fire projections. Meteorological operations and research in the United States are working to provide for these needs of fire planners.

Models are being developed to forecast 30-day fire potential in the contiguous United States and Alaska. Specification equations have been developed to make 30-day forecasts of the anomalies (departure from the mean) of these variables: (a) the 1300 LST temperature (T), dewpoint (Td), and windspeed (W) at 116 National Weather Service (NWS) stations; and (b) the precipitation frequency (PF) at 60 climate areas in the contiguous United States (Klein and Whistler 1989). PF is defined as the number of days in the month on which the precipitation is equal to or greater than 2.54 mm. The input to the specification equations will be as follows: (a) the 30-day prognostic 700 mb height anomalies at 121 grid points prepared by the NWS Climatic Analysis Center and (b) the previous month's anomaly of the dependent variable; i.e., T, Td, or W. The specification equations were developed using the "perfect prog" technique described by Klein (1982), where coarse climatological data (30-day prognostic 700 mb height anomalies and previous month's dependent variable) are related to local weather data (T, Td, or W). These 30-day forecasts of T, Td, W, and PF will be used to calculate those weather-driven fire indices best correlated with measures of fire activity on nearby National Forests (McCutchan and Main 1989).

The 20 years of data for the 116 stations that were used to develop specification equations are also being used to calculate empirical distribution functions of

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

the nine monthly meteorological variables and weather-driven fire indices for the 116 stations (Hogg and Tanis 1977). For example, the anomalies of the particular variable or index for each of the 20 years of data are sorted from lowest to highest value. Then the 5th percentile is assigned to the lowest value, 10th percentile to the next, etc., and finally 100th percentile is assigned to the highest value of the anomalies. This procedure provides percentiles of the anomalies of the variables and indices. These percentiles are determined completely by climatology. For example, a 90th percentile anomaly would equal or exceed 90 percent of the anomalies in the climatological record. The 30-day forecast anomalies of the meteorological variables and weather-driven fire indices for each of the 116 NWS stations would be compared with the empirical distribution functions at the respective stations to determine the 30-day forecast percentiles. The forecast percentiles for the 116 stations would then be computer plotted and analyzed.

This paper reports on the development of multiple regression equations to interpolate fire potential forecasts from nine NWS stations in and around California to 31 fire weather stations located in mountainous terrain of California (Fig. 1). This spatial interpolation would allow more accurate analyses of the regional variations in fire potential forecasts.

Methods

Surface weather observations at 1300 PST were obtained at nine NWS stations for the 20-year period, 1964-1983, and at 31 fire weather stations for the 19 years, 1964-1970 and 1972-1983 (Fig. 1.). About one half of the fire weather stations had data for only the fire season, May through October. We first computed monthly mean values of temperature (°F), dewpoint (°F), relative humidity (%), and windspeed (mph). We then used the monthly mean values of the four meteorological variables to compute monthly values of five weather-driven fire indices best correlated with measures of fire activity on nearby National Forests (McCutchan and Main 1989). The indices are these:

1. Equilibrium Moisture Content (m) (Simard 1968)

$$m = 0.03229 + 0.28107(RH) - 0.00057(RH)(T) \quad \text{for } RH \le 10\% \tag{1a}$$

$$m = 2.22749 + 0.160107(RH) - 0.014784(T) \quad \text{for RH; } 11\% \le RH \le 50\% \tag{1b}$$

$$m = 21.0606 + 0.005565(RH)^2 - 0.00035(RH)(T) - 0.483199(RH) \quad \text{or } RH > 50\% \tag{1c}$$

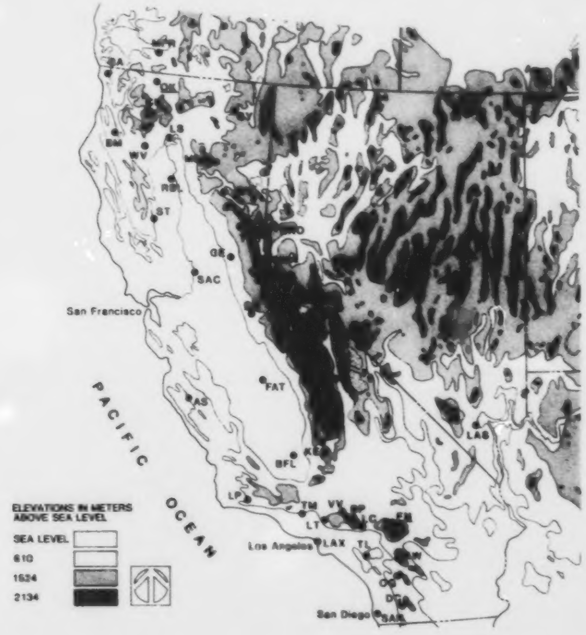


FIG. 1. Locations of 9 National Weather Stations (three-character identifiers) and 31 fire weather stations (two-character identifiers) in and around California. The two-character identifiers for Oak Knoll (OK), Groveland (GR), and Fawnskin (FN) are underlined.

where T is the monthly mean temperature (°F), and RH is the monthly mean relative humidity (%).

2. Fire Weather Index (FWI) (Fosberg 1978)

$$FWI = n\ (1 + W^2)^{1/2}/0.3002 \tag{2}$$

where W is the monthly mean windspeed (mph), and n is a moisture damping coefficient defined as

$$n = 1 - 2\ (m/30) + 1.5\ (m/30)^2 - 0.5\ (m/30)^3 \tag{3}$$

where m is the equilibrium moisture content.

Three other indices (Chandler et al. 1983)

3. Intensity Component (I)

$$I = (110 - 1.373(RH)) - 0.54(10.2-T) \tag{4a}$$

4. Spread Component (S)

$$S = 124 \times 10^{-0.0142(RH)} \tag{4b}$$

5. Burning Index (BI)

$$BI = (I)(S)/60 \tag{4c}$$

where T is monthly mean temperature (°C), and RH is monthly mean relative humidity (%).

Model Design and Results

Nine of the 116 NWS stations are located in and around California at airports near major cities (Fig. 1); however, much of California is covered by mountainous terrain. For example, analysis of percentiles of the anomalies in observed monthly mean temperature for July 1980 that is based solely on the nine NWS stations shows little or no effect of the mountainous terrain (Fig. 2a). However, when the analysis is based on both the nine NWS stations and the 31 fire weather stations, the effect of the mountainous terrain is apparent (Fig. 2b). Therefore, spatial interpolation of the fire potential forecasts from the nine NWS stations to the 31 fire weather stations is necessary for more accurate analysis of the forecasts in the mountainous terrain of California.

Anomalies were computed for the four meteorological variables and the five fire indices at the nine NWS stations and 31 fire weather stations. Regression equations are being developed to interpolate anomalies of the variables and indices to the 31 fire weather stations for all months of the year where data are available. The equations are of the form:

$$y_j = b_o + \sum_{i=1}^{9} b_i x_{ij} + \epsilon_j \tag{5}$$

where y_j is the monthly mean anomaly of the variables and indices for the jth year at the fire weather stations, x_{ij} is the monthly mean anomaly of the variables and indices at the ith NWS station for the jth year, and ϵ_j is the residual error and is assumed independent and normally distributed with mean zero and variance σ^2.

For this paper, all possible subset regressions (SAS 1985) were used to develop regression models and to interpolate anomalies of temperature, relative humidity, and windspeed and either intensity component or burning index from nine NWS stations to three of the 31 fire weather stations for the months of January and July. The three stations are Oak Knoll Ranger Station (OK) in northern California; Groveland Ranger Station (GR) in central California; and Fawnskin Fire Station (FN) in southern California (Table 1, Fig. 1).

All possible subset regressions were used to select subsets of one, two, three, and four predictors using Eq. 5 (Table 2). We considered only subsets of four or less to avoid overfitting the data. The predictands were anomalies of the monthly mean 1300 PST temperature, relative humidity, windspeed, and the Intensity Component or Burning Index at the three fire weather stations. The nine possible predictors were anomalies of the respective variables/indices at the nine NWS stations. To determine if a subset of one, two, three, or four predictors was used in the interpolation model, we arbitrarily used an increase of 0.04 in R^2 as the cut-off criterion. For example, at Oak Knoll, the regression equation for interpolating the 1300 PST monthly mean temperature anomaly for

Table 1. Characteristics of three fire weather stations and nine National Weather Service stations.

Name	ID	Latitude	Longitude	Elev (m)
	Fire Weather Stations			
Oak Knoll Ranger Station, Klamath National Forest	OK	41.83	122.94	518
Groveland Ranger Station, Stanislaus National Forest	GR	37.83	120.24	975
Fawnskin Fire Station, San Bernardino National Forest	FN	34.30	116.90	2088
	National Weather Service Stations			
Bakersfield, CA	BFL	35.39	119.00	150
Fresno, CA	FAT	36.73	119.78	100
Las Vegas, NV	LAS	36.18	115.11	664
Los Angeles, CA	LAX	34.00	118.40	32
Medford, OR	MFR	42.32	122.88	405
Red Bluff, CA	RBL	40.17	122.23	107
Reno, NV	RNO	39.54	119.80	1341
Sacramento, CA	SAC	38.56	121.48	8
San Diego, CA	SAN	32.74	117.19	9

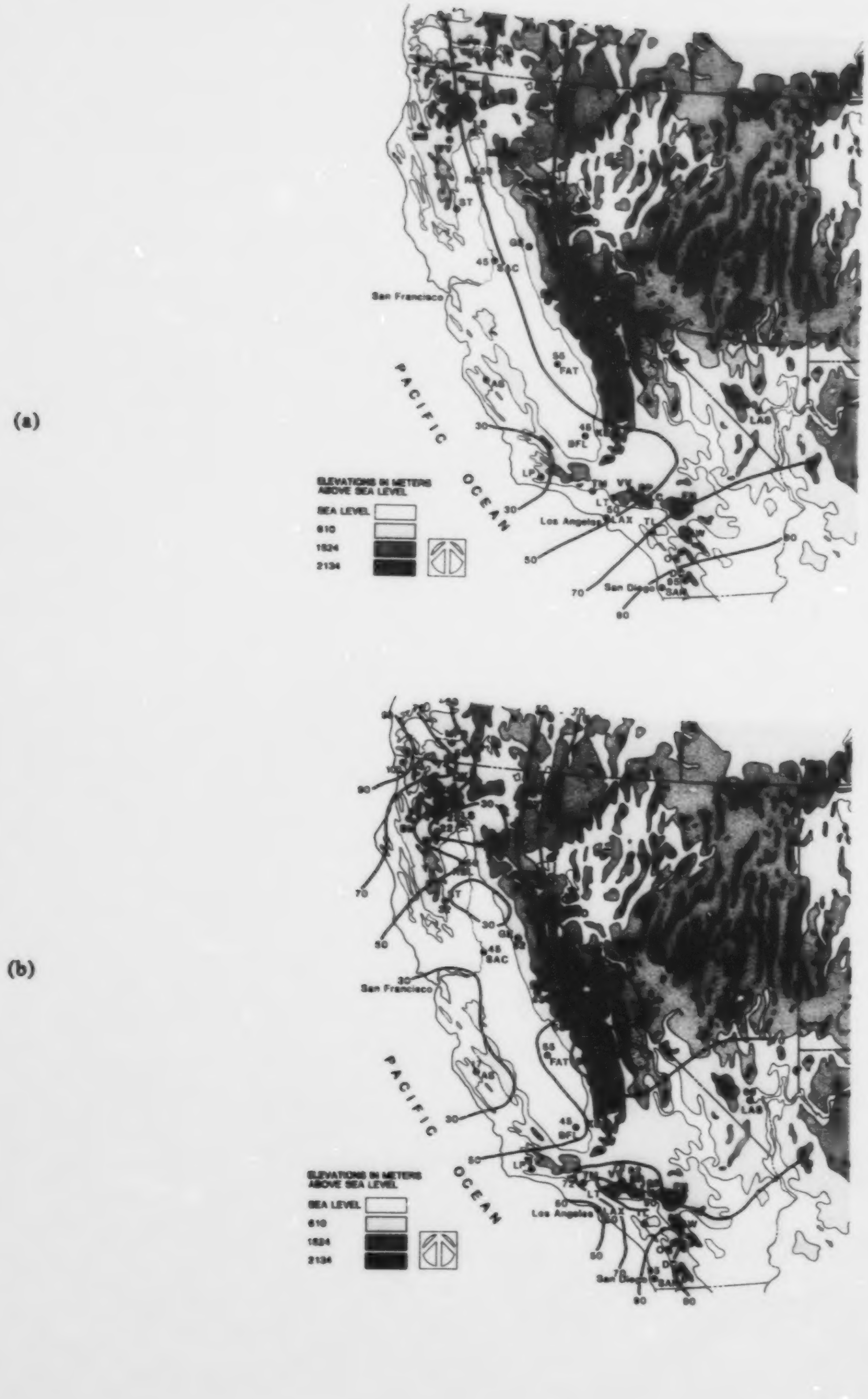

(a)
PACIFIC OCEAN
San Francisco
SAC
FAT
BFL
LAS
Los Angeles
LAX
San Diego
SAN
ELEVATIONS IN METERS ABOVE SEA LEVEL
SEA LEVEL
610
1524
2134
30
45
50
55
70
80
90
(b)
PACIFIC OCEAN
San Francisco
SAC
FAT
BFL
LAS
Los Angeles
LAX
San Diego
SAN
ELEVATIONS IN METERS ABOVE SEA LEVEL
SEA LEVEL
610
1524
2134
30
45
50
55
60
70
90

FIG. 2. Analyses of percentiles of the temperature anomalies for July 1980 were based on: (a) nine NWS stations, and (b) nine NWS stations and 31 fire weather stations.

January has two predictors--the temperature anomalies Medford, Oregon (MFR) and Reno, Nevada (RNO) (Table 2, Fig. 1). Note that the first predictor (MFR) explained 65 percent of the temperature variance at Fawnskin, the second predictor (RNO) increased the R^2 by 25 percent, but the increase for a subset of three predictors was 1 percent. The standard error of estimate shows the precision of the interpolation. In July, the relative humidity and the burning index at Oak Knoll had the same subset of predictors. The same was true for Fawnskin. In addition, the relative humidity and the intensity component at Groveland in July had the same subset of predictors. Furthermore, at all three stations the R^2 values were the same or similar.

The R^2 values for interpolating the three variables and one index to the three fire weather stations were lowest for these variables: (a) windspeed in July at Oak Knoll (0.37) and in January at Fawnskin (0.43), and (b) relative humidity (0.41) and intensity component (0.43) in January at Groveland. The R^2 values were highest for these variables: (a) windspeed in January at Oak Knoll (0.93), and (b) temperature in January also at Oak Knoll (0.90).

Once we selected the predictor subset, we determined the regression equation. For example, at Fawnskin, the regression equation developed for the anomaly of the burning index for July had three predictors--the 30-day forecast anomaly of the 1300 PST monthly mean burning index at Las Vegas, Nevada (LAS); Fresno, California, (FAT); and Reno, Nevada (RNO) (Table 3, Fig. 1). After determining the interpolated value of the anomaly at Fawnskin, we compared it with the empirical distribution function of the burning index at Fawnskin to determine the interpolated percentile (Fig. 3). For example, if the anomaly is 20.0, the percentile would be 84.5.

Table 3. Regression model for interpolating the anomaly of the 1300 PST monthly mean burning index for July to Fawnskin Fire Station in southern California.

Burning Index	Coefficient	R2	S.E.E.
Constant	-0.600	0.85	8.85
Las Vegas, NV	0.620		
Fresno, CA	-0.826		
Reno, NV	0.428		

Conclusions

Analysis of percentiles of the temperature anomalies for July 1980, which was based on 9 NWS stations and 31 fire weather stations, showed large regional variations. These results demonstrate the necessity for interpolating fire potential forecasts from the NWS stations to fire weather stations located in complex mountainous terrain in California. This will allow for more accurate analyses and mapping of fire potential forecasts.

The R^2 values for interpolating temperature, relative humidity, windspeed, and intensity component or burning index to Oak Knoll Ranger Station in northern California, Groveland Ranger Station in central California, and Fawnskin Fire Station in southern California ranged from a low of 0.37 for windspeed in July at Oak Knoll to a high of 0.93 for windspeed in January, also at Oak Knoll. Therefore, the monthly mean anomalies of temperature, relative humidity, windspeed, and intensity component and/or burning index can be successfully interpolated from the NWS stations to the fire weather stations in the mountainous terrain of California. Monthly and spatial differences in accuracy, however, are marked.

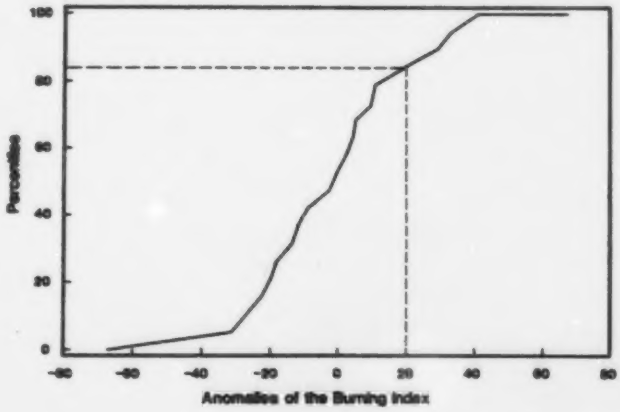


FIG. 3. Empirical distribution function of anomalies of the monthly mean burning index for July at Fawnskin Fire Station for 1963-1969 and 1971-1983.

Table 2. Results of the all possible subset regressions for January and July at three fire weather stations in California. The predictands are monthly mean anomalies of the temperature, relative humidity, windspeed, and burning index or intensity component at the fire weather station. The predictors are the anomalies of the respective variable and index at the specified National Weather Service stations. The subset of predictors selected for the regression equations is indicated by an asterisk. S.E.E. is standard error of estimate.

Oak Knoll Ranger Station (OK), northern California

	January						July					
Y	X1	X2	X3	X4	R^2	S.E.E.	X1	X2	X3	X4	R2	S.E.E.
Temperature	MFR				.65	3.30	MFR				.70	1.98
	*MFR	RNO			.90	1.91	*MFR	RNO			.76	1.84
	MFR	RNO	LAX		.91	1.91	MFR	RNO	BFL		.78	1.80
	MFR	RNO	LAX	FAT	.98	.94	MFR	RNO	BFL	SAC	.81	1.75
Relative Humidity	RNO				.29	9.11	MFR				.54	2.51
	MFR	LAS			.43	8.86	*MFR	RNO			.65	2.27
	MFR	LAS	FAT		.71	6.92	MFR	RNO	BFL		.68	2.25
	*MFR	LAS	FAT	BFL	.76	6.97	MFR	RNO	BFL	LAS	.72	2.16
Windspeed	FAT				.56	.83	MFR				.13	1.09
	FAT	BFL			.72	.72	MFR	SAC			.32	.99
	*FAT	BFL	SAC		.93	.39	*MFR	SAC	SAN		.37	.98
	FAT	BFL	SAC	LAX	.95	.35	MFR	SAC	SAN	FAT	.40	.99
Burning Index	LAS				.27	3.95	MFR				.54	11.38
	LAS	FAT			.52	3.46	*MFR	RNO			.65	10.14
	*LAS	FAT	MFR		.75	2.73	MFR	RNO	BFL		.67	10.19
	LAS	FAT	MFR	BFL	.77	2.92	MFR	RNO	BFL	LAS	.70	10.00

Groveland Ranger Station (GR), central California

	January						July					
Y	X1	X2	X3	X4	R^2	S.E.E.	X1	X2	X3	X4	R^2	S.E.E.
Temperature	SAN				.47	2.89	BFL				.72	1.29
	SAN	FAT			.54	2.83	*BFL	MFR			.76	1.22
	*SAN	FAT	MFR		.70	2.40	BFL	MFR	FAT		.77	1.23
	SAN	FAT	MFR	RBL	.73	2.37	BFL	MFR	FAT	LAX	.78	1.26
Relative Humidity	SAC				.10	11.10	RBL				.35	3.30
	SAC	BFL			.18	11.06	RBL	FAT			.50	3.00
	SAC	BFL	LAS		.36	10.24	RBL	FAT	RNO		.55	2.92
	*SAC	BFL	LAS	SAN	.41	10.40	*RBL	FAT	RNO	LAS	.64	2.71
Windspeed	MFR				.29	1.46	FAT				.24	1.66
	MFR	LAS			.41	1.39	FAT	SAC			.48	1.42
	MFR	LAS	RBL		.51	1.33	FAT	SAC	BFL		.66	1.18
	*MFR	LAS	RBL	FAT	.58	1.29	*FAT	SAC	BFL	RNO	.76	1.03
Intensity Component	LAS				.10	16.14	RBL				.38	4.77
	LAS	BFL			.22	15.69	RBL	FAT			.52	4.33
	LAS	BFL	SAC		.38	14.59	RBL	FAT	RNO		.57	4.21
	*LAS	BFL	SAC	SAN	.43	14.85	*RBL	FAT	RNO	LAS	.65	4.03

Table 2. (Continued)

Fawnskin Fire Station (FN), southern California

	January						July					
Y	X1	X2	X3	X4	R^2	S.E.E.	X1	X2	X3	X4	R^2	S.E.E.
Temperature	LAX				.43	3.51	LAS				.54	1.50
	LAX	SAN			.66	2.83	*LAS	FAT			.76	1.12
	LAX	SAN	LAS		.80	2.24	LAS	FAT	BFL		.77	1.15
	*LAX	SAN	LAS	MFR	.87	1.88	LAS	FAT	BFL	SAC	.77	1.16
Relative Humidity	LAX				.51	10.65	LAS				.77	3.00
	LAX	FAT			.56	10.46	LAS	FAT			.83	2.63
	*LAX	FAT	SAC		.66	9.55	*LAS	FAT	RNO		.88	2.32
	LAX	FAT	SAC	MFR	.68	9.62	LAS	FAT	RNO	MFR	.89	2.29
Windspeed	FAT				.12	1.45	LAS				.34	1.70
	FAT	RBL			.27	1.38	LAS	LAX			.65	1.27
	FAT	RBL	RNO		.38	1.32	*LAS	LAX	MFR		.78	1.05
	*FAT	RBL	RNO	LAS	.43	1.32	LAS	LAX	MFR	BFL	.81	1.01
Burning Index	LAX				.47	14.08	LAS				.75	10.63
	LAX	RNO			.53	13.72	LAS	FAT			.80	9.80
	*LAX	FAT	RBL		.62	12.83	*LAS	FAT	RNO		.85	8.81
	LAX	FAT	RBL	RNO	.66	12.78	LAS	FAT	RNO	LAX	.87	8.43

*The subset selected showed an increase in R^2 of ≥ 0.04

References

CHANDLER, C., P. CHENEY, P. THOMAS, L. TRABAUD, AND D. WILLIAMS. 1983. Fire in Forestry. John Wiley & Sons. 450 p.

DEEMING, J. E., 1987. Fire-danger rating. The next 20 years. P. 66-72. In Proc. Symp. on Wildland Fire 2000. 1987 April 27-30, South Lake Tahoe, CA. Gen. Tech. Rep. PSW-101. USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Berkeley, CA.

FOSBERG, M. A. 1978. Weather in wildland fire management: the fire weather index. P. 1-4. In Proc. of the Conf. on Sierra Nevada Meteor., South Lake Tahoe, Calif.

HOGG, R. V. AND E. A. TANIS. 1977. Probability and Statistical Inference. Macmillian Publishing Co. Inc. New York, 449 p.

KLEIN, W. K. 1982. Statistical weather forecasting on different time scales. Bull. Amer. Meteor. Soc. 63:170-177.

KLEIN, W. K. AND B. T. WHISTLER. 1989. Specifying monthly mean anomalies of fire weather elements from concurrent anomalies of the mean 700 mb height field. In Proc. 10th Conf. on Fire and Forest Meteor. Ottawa, Ontario., Apr. 17 - 21, 1989.

MCCUTCHAN, M. W. AND W. A. MAIN. 1989. The relationship between mean monthly fire potential indices and monthly fire severity. In Proc. 10th Conf. on Fire and Forest Meteor. Ottawa, Ontario, Apr. 17 - 21, 1989.

SAS. 1985. The RSQUARE procedure, SAS User's Guide: Statistics. Version 5 Edition. SAS Institute Inc., Cary, NC, 956 p.

SIMARD, A. J. 1968. The moisture content of forest fuels. I. A review of the basic concepts. For. Fire Res. Inst. Inf. Rep. FF-X-14.

Forecasting Wildfire "Blow Up"

B. B. ARONOVITCH
National Weather Service Office For Fire Weather
Olympia, Washington

Abstract

Two energy-criterion equations are given for P_f and P_w, the rate of conversion of thermal energy to kinetic energy per unit area in the column of a wildfire, and the rate of flow of kinetic energy in the wind field above that fire respectively. When $P_f \geq P_w$ the wildfire assumes three-dimensionality, i.e., "blows up", and becomes a free-convection phenomenon controlled by itself, as opposed to a forced-convection one controlled by the wind. The most favorable condition for this to occur is the existence of a low-level jet, sometimes referred to as a negative wind profile. Ground and aerial data from the Butte and Sundance fires in Idaho, August, 1985 and September, 1967 respectively, were applied to the above-mentioned equations resulting in predicted fire behavior characteristics closely resembling those observed on the fires. Hence it may be possible to routinely forecast whether or not a wildfire will indeed blow up, and if so, approximately when, along with an approximate profile of that fire's column. Such advice would be very useful to wildfire control agencies.

Résumé

Deux équations de critères d'énergie sont présentées pour P_f et P_w, représentant respectivement le taux de conversion de l'énergie thermique en énergie cynétique par unité de superficie dans la colonne d'un feu de friches et le taux de transfert de l'énergie cynétique dans le champ de vent à une certaine hauteur au-dessus du feu. Lorsque $P_f \geq P_w$, le feu feu de friches devient tridimensionnel, c-a-d. qu'il "explose" et devient un phénomène de convection libre autocontrôlé et non pas de convection forcée contrôlée par le vent. La condition la plus propice à l'apparition de ce phénomène est l'existence ou l'arrivée d'un courant-jet de basse altitude, souvent appelé profil négatif du vent. Les données prélevées au sol et dans les airs lors des incendie de Butte en Idaho en août 1985 et du feu de Sundance en septembre 1967 ont été appliquées aux équations susmentionnées, donnant des prévisions des caractéristiques du comportement du feu ressemblant de près à celles observées lors de ces incendies. Par conséquent il peut être possible de prévoir régulièrement si un feu de friches "explosera" ou non et, dans l'affirmative, à quel moment à peu près ainsi qui un profil approtimatif de la colonne de ce feu. De tels conseils pourraient être extrêmement utiles aux organismes de lutte contre les feu de friches.

Introduction

Thirty years ago, Byram (1959) introduced two energy-criterion equations for the rate of flow of kinetic energy per unit area of the wind field above a wildfire and for the rate of conversion of thermal energy to kinetic energy per unit area in the column of the fire. The equations never achieved the popularity they deserved because little was known about the energy produced in a wildfire. However, research since then has revealed much about that energy and led to the National Fire Danger Rating System, and a program called "BEHAVE". Intensity of a wildfire is now routinely available.

High intensity or blow up fires can exceed 20,000 BTU per foot per second, and have vertical structures that can reach 25,000 feet or more. Such characteristics more closely resemble those of thunderstorms than of fires. However, conditions may exist under which a high intensity two-dimensional fire may form a convection column intermittently and, more important, such large-scale characteristics may appear very suddenly and unexpectedly on small fires. It is to these two points that this paper is addressed.

Since large fires display characteristics similar to those of thunderstorms it is possible to reduce a large fire to an energy-related fire system model, much as one does for a thunderstorm. Such a model facilitates the use of mathematical methods to understand and forecast fire behavior through energy conversion processes. It is possible to mathematically compare the rate of energy flow in the wind field above a fire to the conversion rate of thermal energy to kinetic energy in the column of that fire.

Byram (1959) derived two equations, for a neutrally-stable atmosphere. They are:

$$P_w = \Gamma(v-r)^3/2g \qquad \text{for the wind field} \qquad (1)$$

$$P_f = I/c_p(T_o + 459) \qquad \text{for the fire} \qquad (2)$$

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

where

P_w	= flow rate of KE/unit area in the windfield	ft-lb sec^{-1} ft^{-2}
r	= rate of fire spread	ft sec^{-1}
g	= acceleration of gravity	ft sec^{-2}
Γ	= air density at height Z	lb ft^{-3}
v	= wind speed at height Z	ft sec^{-1}
Z	= some height above the fire	ft
r	= rate of fire spread	ft sec^{-1}
P_f	= conversion rate of thermal energy to KE/unit area in the column	ft-lb sec^{-1} ft^{-2}
I	= fire intensity	BTU ft^{-1} sec^{-1}
c_p	= specific heat of air at constant pressure	BTU lb^{-1} °F^{-1}
T_o	= free-air temperature at fire elevation	F

Fire intensity, I, in Eq. 2, is the product of the forward rate of spread and the heat of combustion of the fuel, and is based on complete combustion. This rarely happens on a rapidly moving fire. However, since

$$I = Hwr \tag{3}$$

where

H	= heat yield per pound of fuel available	BTU lb^{-1}
w	= weight of available fuel per square foot	lb ft^{-2}

(2) may be rewritten as

$$P_f = Hwr/c_p(T_o + 459) \tag{4}$$

For a moving fire to build to a high-intensity, 3-dimensional fire, P_f must become larger than P_w. This puts stringent restrictions on the surface and upper winds. In order to build to a high intensity, considerable wind at or near the surface is required, since high winds increase the rate of fire spread (r). Slope effect may replace wind while fire is making an uphill run, but this effect is of limited duration. As P_f increases and approaches the value of P_w in the lower levels near the fire, the condition that is most favorable for the explosive growth of a convection column is that P_f be greater than P_w at higher levels. The wind profile that best meets that requirement is the existence, or onset, of a low-level wind maximum at or slightly above the fire elevation, sometimes referred to as a negative wind profile. It is not surprising that such jets are repeatedly associated with many fires, such as those described by Byram (1959), Rothermel and Gorski (1986) and Anderson (1968).

Figs. 1a-d and 3c give examples of wind profiles from fire blow ups. These examples suggest a preferred wind maximum elevation from the surface to about 2,000 feet above the fire elevation. Byram (1959) suggests that the wind maximum may be as low as 12 mph for P_f to become larger than P_w.

When P_f is greater than P_w, the fire-wind system is dominated by the energy of the fire, i.e., the energy conversion rate in the column exceeds the rate of flow of kinetic energy in the windfield, and the fire assumes a vertical or 3-dimensional structure. Erratic fire behavior characteristics will then be evident. One of the most erratic conditions occur in the transition zone where an increasing P_f first equals, then exceeds P_w. The results are:

1. The fire changes from a 2-dimensional to a 3-dimensional phenomenon (it acquires vertical structure).
2. The fire changes from forced-convection driven by the wind, to free-convection driven by itself.
3. The fire acquires a chimney, or convection column, instead of a plume.
4. The fire blows up.

Since 3-dimensional fires depend on meteorological information, fire weather forecasters may provide an additional service to fire control agencies. Through meteorological forecasts of wind and temperature, we may also be able to forecast the time when P_f becomes greater than P_w.

Calculation of P_f and P_w

To reduce the number of operational (real-time) calculations of the various elements in Eqs. 1 and 2, some approximations can be made which might reasonably be considered as constants. We establish the boundaries of these approximations by considering that most forest fires occur between sea level and 8,000 feet msl (or 750 mb) in most western states, and generally when the temperature is between 70 and 100°F. Fires also require relative humidity which is generally below 30%. Using these boundaries, three elements in Eqs. 1 and 2 become candidates as approximate constants (Hess 1959 and Smithsonian Meteorological Tables 1963). They are density, gravity and specific heat.

The BEHAVE program, an offshoot of the National Fire Danger Rating System, was designed for field use by fire behavior analysts (FBAs). It generates a host of outputs used by FBAs, one of which is intensity, I, using a set of inputs such as fuel model (local specie, H, in Eq. 4), fuel loading (amount of fuel available, w, in Eq. 4), and spread rate (r in Eqs. 1 and 4), via slope factor and surface wind speed. Intensity, I, may then be observed or forecast. This is the same intensity required in Eq. 2. T_o may be obtained from a pilot or a sounding and wind speeds aloft (v in Eq. 1) may be obtained from a pibal or rawinsonde observation.

P_f and P_w may be calculated from the above data. Both observed and forecast relationships have important implications for wildfire and its behavior. For example, FBAs anticipate the possibility of a blow up

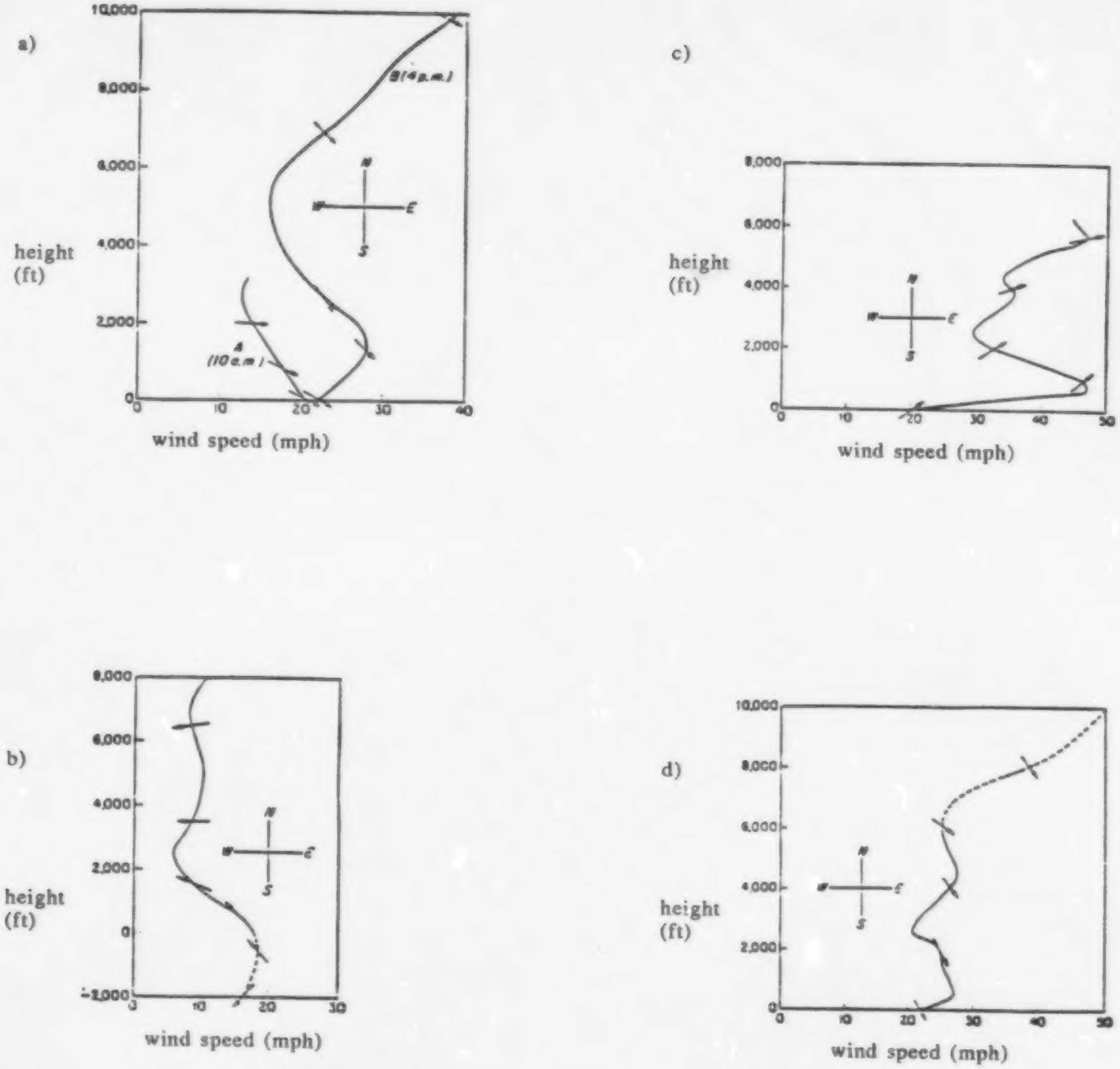


FIG. 1 Wind profiles with time and space proximity of blow-up fires for a) The 10/23/53 Fort Lewis fire, Roanoke, VA., b) The 8/31/54 Jamison fire, Camp Pendleton, CA., c) The 7/14/54 Chatsworth fire, Philadelphia, PA., and d) The 5/2/51 Wood River Valley Fire, Hartford, CT. The ordinate shows the height above the fire in feet; the mantissa indicates the wind speed in miles per hour.

based entirely on ground data such as fuel moisture, fuel model, fuel loading and surface wind speed. However, their judgement, computerized or not, remains a subjective "gut feeling", rather than an objective analysis of the relationship of P_f to P_w. The tendency to predict blow up probably increases linearly with increasing surface winds; however, it is most unlikely that a two-dimensional fire will become 3-dimensional unless the required vertical wind profile is present, one which allows P_f to equal, then exceed P_w[1].

Operationally, the positioning of firefighters and equipment is critically dependent upon whether or not a fire will blow up.

Some major wildfires acquire a convection column on a daily basis, probably when ground conditions remain fairly constant from day to day, and P_f/P_w, henceforth defined as the convection number Nc, is nearly equal to or slightly less than 1. Sometimes a fire may appear to blow up more than once a day. For example, if Nc is a little less than 1, but a fire begins an uphill run, the slope effect would be equivalent to increasing the wind speed "at or near" the surface. This, in turn, would have the effect of reducing the relative wind speed above the fire, resulting in Nc temporarily becoming greater than 1. A comparison of P_f to P_w might show, however, the temporary nature of the condition. Such a comparison is quite useful when a potentially dangerous two-dimensional fire running uphill gives the appearance that it is about to blow up. One may conclude that both observed and forecast values of Nc are useful (as shown in Fig. 2), particularly when winds aloft are fairly light.

Nc on the Butte Fire, Idaho, Aug. 29, 1985

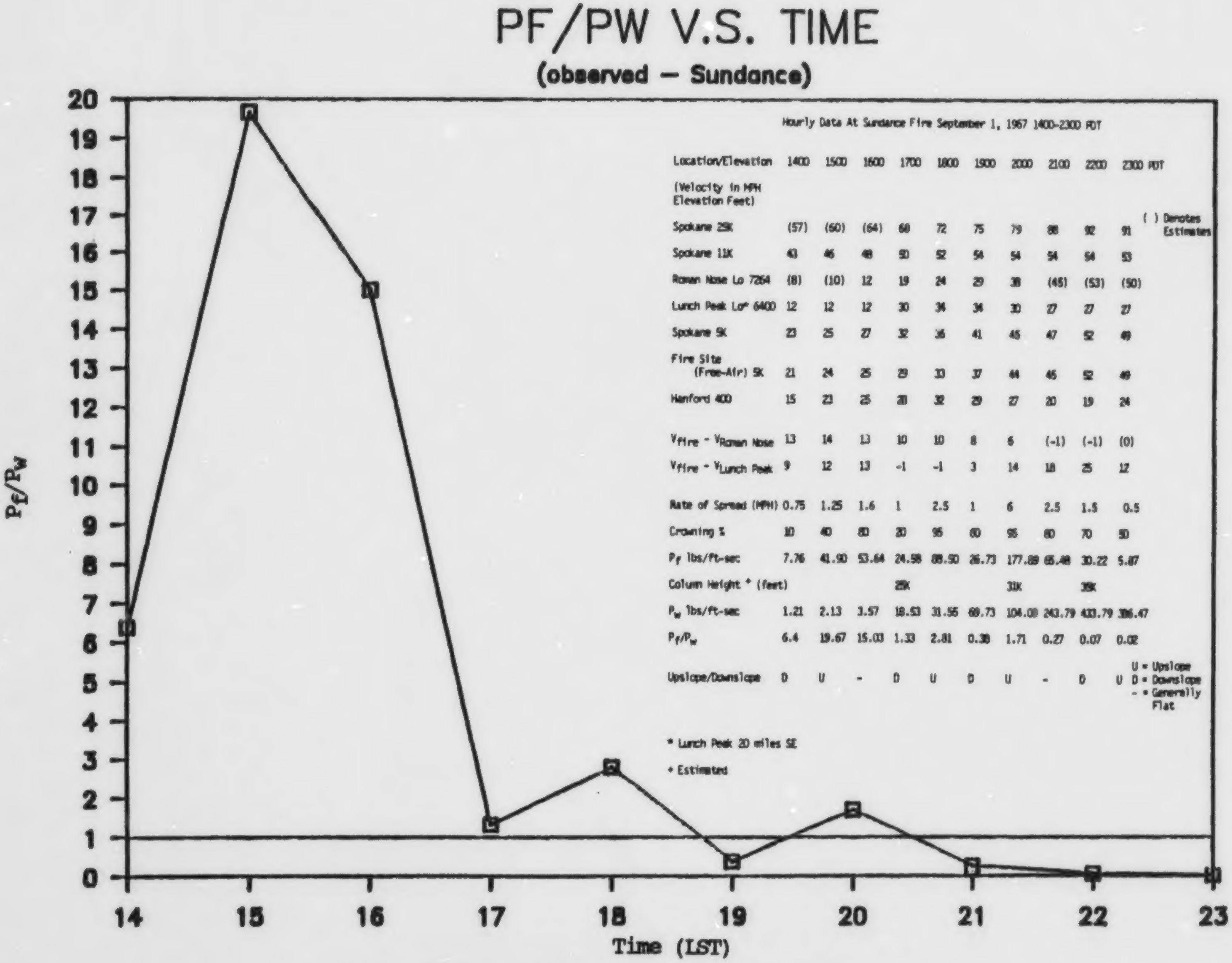
Ground and aerial conditions were similar August 27th, 28th and 29th with the exception of the wind profile during the afternoon of the 29th, which became negative to about 2,500 feet above the fire (Figs. 3a-c). The fire blew up during that afternoon, placing 73 firefighters in a life-threatening situation. It was only the deployment of their fire shelters that saved them.

P_w was calculated for each 100 feet of elevation and compared to a constant[2] P_f (Fig. 4), using ground and aerial data obtained from Rothermel and Gorski (1986), Rothermel and Mutch (1986), and Smith (1985) and substituted in Eqs. 1 and 2. Their relative values were plotted as indicated in Figure 5. The horizontal value indicates Nc as a function of elevation. The quasi-vertical line is defined as a "pressure" curve. Using calculations at each 100-foot interval, the slope of the pressure curve in each interval is determined by the relative magnitudes of P_f and P_w for the vertical and horizontal directions, respectively. The resultant vector sum is the plotted trajectory of that particle. As such, the results should represent the profile of the smoke column.

The "pressure" curve indicates that the top of the column is near 13,500 feet agl. The reported estimate of the column was about 16,000 feet, about 2,500 feet higher than that indicated in Fig. 5. The difference may be explained by the fact that P_f was calculated for a neutrally-stable atmosphere. It is, therefore, a horizontal line when plotted as a function of elevation. However, the atmosphere was unstable in the lower layers. Byram (1959) states that P_f would curve slightly upward for an unstable atmosphere. The convection column would therefore rise to a higher elevation before bending over in response to a decreasing Nc. One may also be able to predict the approximate height of the convection column, which probably relates directly to the degree of erratic, thus dangerous, behavior of a wildfire. Since the "pressure" curve can be plotted given the necessary input data, column profiles can be made available for comparison of one fire under a different set of conditions, or for several fires, each with its own set of conditions. This may prove useful for priority selection (resource distribution) should the need arise.

Nc on the Sundance Fire, Idaho, August 29 - September 1, 1967

Figure 6 depicts the progress of a 40+ mph jet at 700 mb for the period 8/29 to 9/2/67, from Quillayute, WA (UIL), to Spokane, WA (GEG), and to Great Falls, MT (GTF). During the critical period between 9/1 at 1700L (local time) and 9/2 at 0600L, the jet axis was rotating around a point near Newport, on the central Oregon coast. The leading edge of the jet, moving southeastward at 14 mph, reached the fire site between 1900L and 2000L (fire report: 37 and 44 mph respectively). Table 1 (see Figure 2 insert) is a compilation of events collected hourly (1400L to 2300L) according to Anderson (1968), together with the calculated Nc for those hours. Nc was greater than 1 between 1400L and 1600L, reaching a maximum of 19.67 at 1500L. It was during that time that the fire truly became 3-dimensional, and the convection column built to a reported height of 25,000 feet msl. The data input into equations 1 and 2 resulted in a plotted column profile of 20,000 feet agl as indicated in Fig. 7 which would put the top of the column about 25,000 msl. Table 1 and Fig. 2 show the direct relationship of Nc to the trends in fire behavior characteristics such as intensity, crowning and spread during the periods that the fire was 3-dimensional. The great extent of the fire was the consequence of two unfortunate events, 1) the blow up of the fire at about 1500L, and 2) the arrival of strong winds at all elevations after 1900L. Hence, the Sundance fire character was one of forced-convection up to blow up time, free-convection for a brief period, then back to forced-convection, with minor perturbations due to slope effect. The final point to note is that the wind speed at Roman Nose lookout was 13 mph lower than that at the fire elevation at blow up time, but increased about 7 mph each hour after 1600L, while at the surface, the rate of increase was only 4 mph each hour. Because the Roman Nose winds were increasing more rapidly than those at the surface, the



Hourly Data At Sundance Fire September 1, 1967 1400-2300 PDT

Location/Elevation (Velocity in MPH Elevation Feet)	1400	1500	1600	1700	1800	1900	2000	2100	2200	2300 PDT
Spokane 25K	(57)	(60)	(64)	68	72	75	79	88	92	91
Spokane 11K	43	46	48	50	52	54	54	54	54	53
Roman Nose Lo 7264	(8)	(10)	12	19	24	29	38	(45)	(53)	(50)
Lunch Peak Lo* 6400	12	12	12	30	34	34	30	27	27	27
Spokane 5K	23	25	27	32	36	41	45	47	52	49
Fire Site (Free-Air) 5K	21	24	25	29	33	37	44	45	52	49
Hanford 400	15	23	25	28	32	29	27	20	19	24
$V_{fire} - V_{Roman\ Nose}$	13	14	13	10	10	8	6	(-1)	(-1)	(0)
$V_{fire} - V_{Lunch\ Peak}$	9	12	13	-1	-1	3	14	18	25	12
Rate of Spread (MPH)	0.75	1.25	1.6	1	2.5	1	6	2.5	1.5	0.5
Crowning %	10	40	80	20	95	60	95	80	70	50
P_f lbs/ft-sec	7.76	41.90	53.64	24.58	88.50	26.73	177.89	65.48	30.22	5.87
Column Height + (feet)				25K			31K		35K	
P_w lbs/ft-sec	1.21	2.13	3.57	18.53	31.56	69.73	104.00	243.79	433.79	386.47
P_f/P_w	6.4	19.67	15.03	1.33	2.81	0.38	1.71	0.27	0.07	0.02
Upslope/Downslope	D	U	-	D	U	D	U	-	D	U

( ) Denotes Estimates

U = Upslope
D = Downslope
- = Generally Flat

* Lunch Peak 20 miles SE

+ Estimated

FIG. 2. Ratio of P_f/P_w during the Sundance fire on 9/1/67 and Table 1 (insert). Hourly data at Sundance fire.

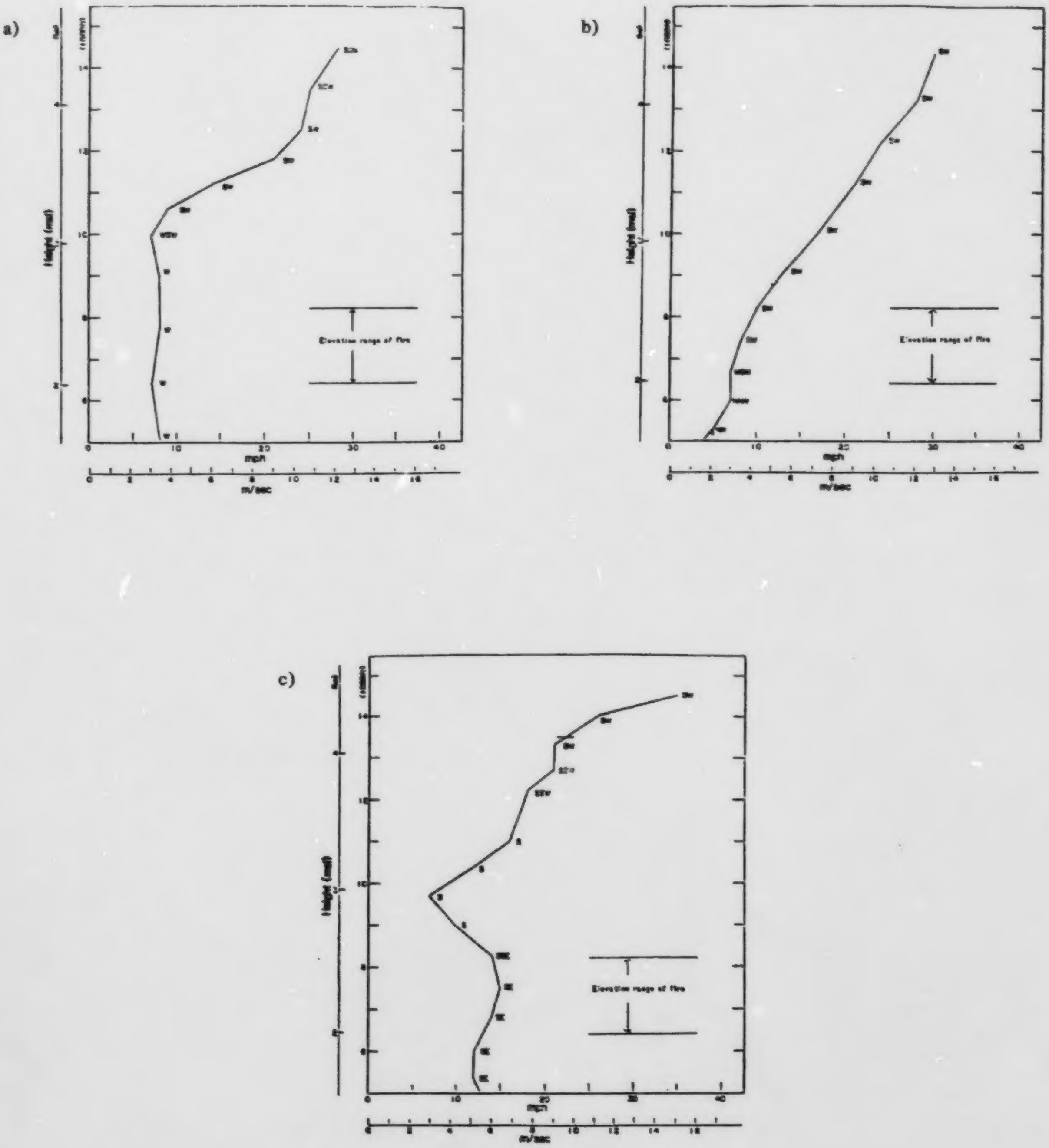


FIG. 3. Boise wind profile at a) 1200Z 8/28/85, b) 1200Z 8/29/85, and c) OOOZ 8/30/85 during the Butte fire.

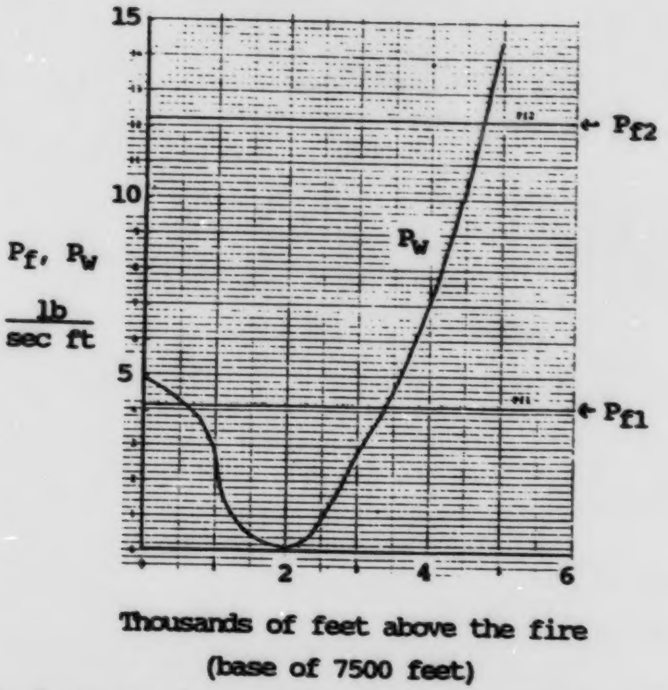


FIG. 4. P_w represents the rate of flow of kinetic energy in the wind field above the Butte fire. P_{f1} represents the energy conversion rate in the convection column prior to blow up. P_{f2} is the conversion rate after blow up.

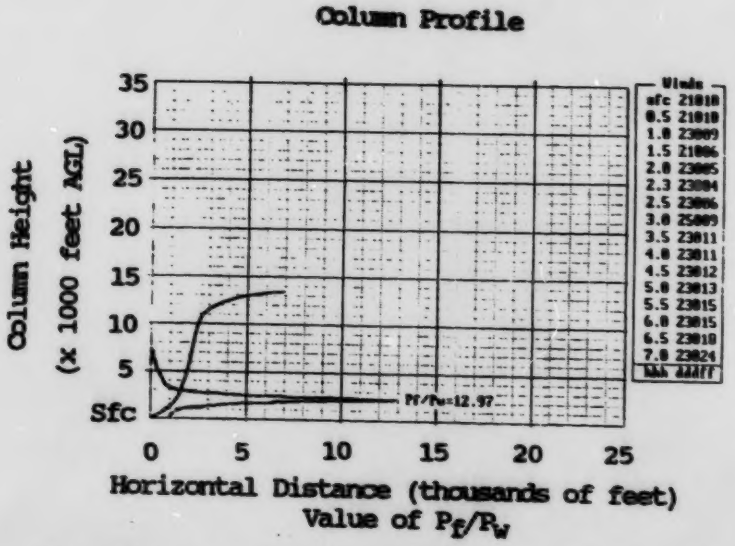
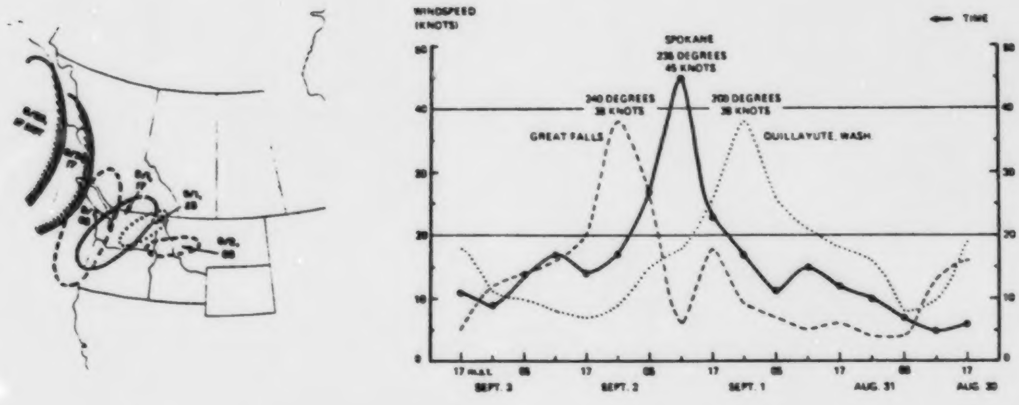


FIG. 5. Parcel trajectory (pressure curve) for Butte fire, 8/29/85.



(a) (b)

FIG. 6. a) Areas of strongest winds (over 40 knots) at 700 mb, in sequence from 1700 MST 8/29/671, 1700 MST 8/31/67, 0500 MST 9/1/67, 1700 MST 9/1/67, 2300 MST 9/1/67, and 0500 MST 9/2/67, and b) a time graph of wind speed between 5000-7000 feet msl at Quillayute (dotted), Spakane (solid), and Great Falls (dashed) from 1700 MST 8/30/67 through 1700 MST 9/3/67. Wind direction is also noted for the maximum speed at each station.

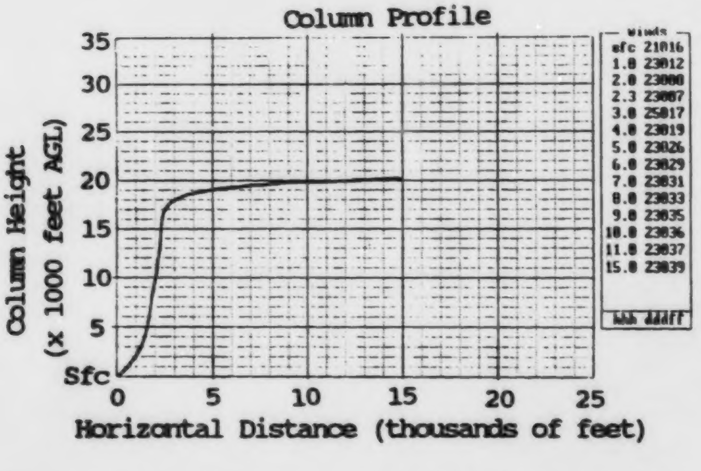


FIG. 7. Parcel trajectory (pressure curve) for Sundance fire, 9/1/67.

negative wind profile weakened and no longer met Byram's criterion of 12 mph for a low-level jet.

Conclusion

Equations 1 and 2, when applied to data from the Butte fire, resulted in close approximation of actual fire behavior, both prior to (morning and early afternoon of the 29th) and after blow up. The same method applied to data from the Sundance fire also resulted in a good approximation of that fire's column. By employing forecast elements in Eqs. 1 and 2, it may be possible to determine whether or not a fire will blow up and if so, the approximate time of that event, along with the expected height of the convection column and the relative degree of erratic fire behavior.

Increasing surface winds (or the addition of a positive slope factor) may cause a fire to increase in intensity. The combination of increasing surface-to-1500 feet agl wind speeds and a negative wind profile above that layer can cause dramatic changes in fire behavior. Similar results may be anticipated whenever light winds aloft are present through a deep layer. This may explain blowups on past fires at times when a low-level jet was not present.

It is strongly recommended that the National Fire Danger Rating System, or at least the BEHAVE program, be modified somehow to include the wind profile above a potential or existing wildfire in order to obtain a better picture of expected fire behavior and fire danger rating. Likewise, FBAs should work closely with meteorologists to routinely apply these concepts to their wildfire forecasts.

---

[1] While fire size and heat release determine the initial column core momentum, atmospheric structure is critical in determining the plume motion (Small and Heikes 1988).

[2] Byram showed that, for a neutrally-stable atmosphere, P_f plotted as a function of elevation, would be a horizontal line, i.e., a constant.

References

ANDERSON, H.E. 1968. Sundance Fire. U.S.D.A. For. Ser. Research paper INT - 56.

BYRAM, G.M. 1959. The Fire System Model. P. 99-107 In K.P. Davis, ed., Forest Fire Control and Use, McGraw-Hill Book Co.

HESS, S.L. 1959. Introduction to Theoretical Meteorology. Holt, Rinehart and Winston, p. 8.

ROTHERMEL, R.C. AND C.J. GORSKI, 1986. Cause of the Butte Fire Blowup. P. 10 - 11, draft, Paper #4.9.

ROTHERMEL, R.C. AND R.W. MUTCH, 1986. Behavior of the Life-Threatening Butte Fire: August 27-29, 1985. In Fire Management Notes, Vol 47, No. 2, 1986.

SMALL, R.D. AND K.E. HEIKES, 1988. Early Cloud Formation by Large Fires. J. Am. Met. 27:654.

SMITH, S.B. 1985. Fire Behavior Summary. Unpublished.

SMITHSONIAN METEOROLOGICAL TABLES, 1963. Sixth Edition.

Méthode de prévision des précipitations pour le calcul des indices canadiens forêt-météo

L. POULIOT
Centre météorologique du Québec
Montréal, Québec

Résumé

La méthode de calcul des indices canadiens forêt-météo exige une précision des hauteurs de pluie qui peut être difficile à obtenir. Dans ce présent ouvrage, nous étudions le facteur pluie, dans un contexte de prévision météorologique, en illustrant les niveaux de précision ou de sensibilité qui affectent les calculs de prévision d'indices. On propose une méthode de conversion des probabilités de pluie en paramètres de hauteurs de pluie nécessaires à la prévision des indices. On décrit brièvement une technique de vérification des précipitations et des indices prévus.

Abstract

The Canadian Forest Fire Weather Index System requires precipitation amounts with an accuracy that can be difficult to attain. In this paper, the rain factor is studied within the weather forecast context, by illustrating the accuracy or sensitivity levels which affect the indices forecast computation. A method is proposed to convert rain probabilities into rain amounts parameters required for the index forecasting. We also give a brief description of a method of verification of the forecast precipitation and indices.

Introduction

Le Centre météorologique du Québec d'Environnement Canada fournit, par son Service Forêt-météo, la prévision météorologique spécifique pour la protection des forêts contre le feu. La prévision Forêt-météo est une prévision qui tient compte, de façon spéciale, de l'incidence des paramètres prévus (météo et indices) sur le développement potentiel des incendies, sur l'identification des zones menacées et sur la planification des ressources nécessaires aux combats des feux. Il est donc essentiel de connaître les seuils critiques des facteurs météo qui influent sur les calculs des indices utilisés comme prédicteurs des incendies de forêt par les organismes de protection des forêts contre le feu. Dans le calcul des indices canadiens forêt-météo (Van Wagner 1987), le paramètre PLUIE représente le facteur le plus important dans l'évaluation des teneurs en eau des combustible forestiers. C'est le seul qui peut abaisser l'indice du combustible disponible (ICD), et il suffit d'une faible quantité de pluie (0,6 mm) pour affecter l'indice d'inflammabilité (ICL). L'ICL, l'ICD et la vitesse du vent permettent d'évaluer les probabilités d'éclosion des incendies de forêt et leur comportement. Dans notre présent ouvrage, nous étudions brièvement le facteur pluie, dans un contexte de prévision météorologique des indices ICL et ICD, en utilisant pour les calculs les équations de la méthode canadienne d'évaluation des danger d'incendie de forêt (Van Wagner et Pickett 1985). Nous décrivons par la suite la technique de prévision des précipitations, développée par le service Forêt-météo, pour la prévision de ces indices.

En tenant compte des précisions des instruments (+/-0,2 mm pour le pluviomètre, +/-5% pour le psychromètre), les calculs de l'ICL ne sont précis qu'à +/-2 unités (plus ou moins une classe d'inflammabilité). Avoir la capacité d'évaluer à une précision de 0,5 mm les précipitations qui affectent une petite région forestière, disons de 10 km par 10 km, à partir d'un seul pluviomètre situé au centre de cette région, nous semble une précision remarquable. Cependant, l'exemple de la figure 1 nous montre que les résultats des calculs d'inflammabilité varieront dans ces conditions de BAS à HAUT. Par conséquent pour la prévision, il est préférable d'évaluer les indices d'une façon spatiale (par zone) plutôt que ponctuelle (par station).

Contrairement à l'ICL, la précision requise pour l'observation de la pluie pour la mesure en général de l'ICD est beaucoup plus facile à obtenir. En se servant des combinaisons (IH et IS) les plus courantes observées durant la saison des feux au Québec, on a calculé pour différents ICD les réductions corres-

---

Présenté au 10 ième Congrès sur les incendies et la météorologie Forestière les 17 au 24 avril 1989 à Ottawa, Canada.

correspondantes en fonction de la pluie. A la figure 2, on voit qu'une réduction d'ICD de 15 unités, à +/- 5 unités près, pour l'ICD 40, est causée par des précipitations de 4 mm à 14 mm, élargissant ainsi les limites de vérification d'une gamme prévue, disons par exemple, de 6 mm à 12 mm. Le facteur pluie d'environ 7 mm pourrait dans ces conditions permettre d'atteindre une précision de 5 unités pour la prévision de l'ICD; précision largement suffisante pour le calcul de l'indice final, L'IFM.

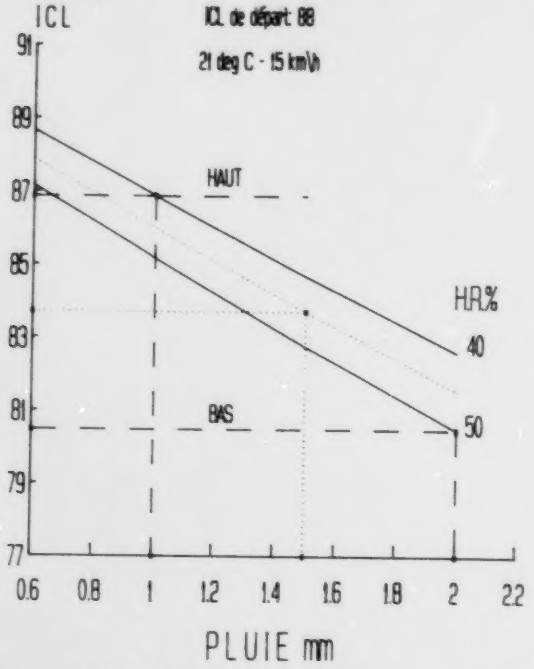


FIG. 1. Précision du calcul de l'ICL en fonction de la pluie et de l'humidité relative.

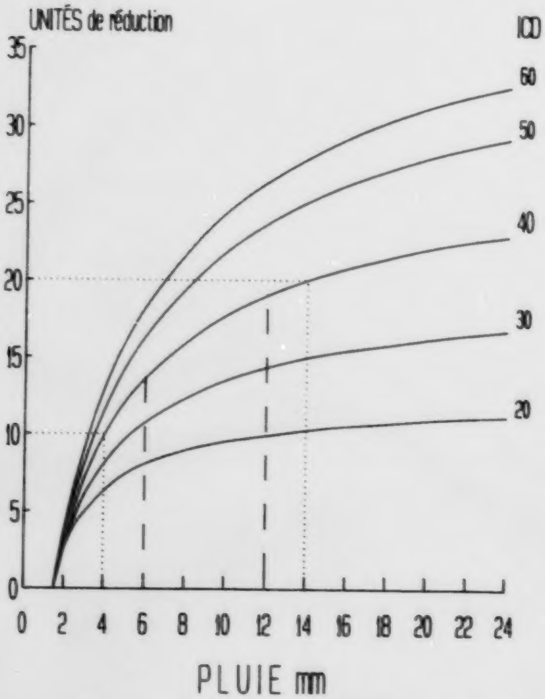


FIG. 2. Réduction de l'ICD en fonction de la pluie.

En étudiant l'effet des différentes hauteurs de pluie dans le calcul des indices, nous nous sommes rendu compte de l'importance relative des précipitations au-delà de certains seuils. Des précipitations de 3 mm premettent d'abaisser l'ICL extrême au niveau NUL ou BAS et de réduire l'ICD d'au moins 5 unités. Après 12 mm, les pentes des courbes de l'ICD s'adoucissent considérablement montrant la faible importance des quantités de pluie excédant cette valeur (voir Turner et Lawson 1978).

Ainsi, par l'analyse des observations, it est souvent possible d'évaluer l'étendue couverte par des précipitations dépassant un seuil minimum donné qui affecte suffisamment les calculs d'indices, en sachant évidemment que la précision de cette évaluation dépendra de la densité du réseau de stations et aussi des systèmes atmosphériques en cause.

Prévision des Précipitations

Pour la prévision des précipitations, nous avons suivi le même raisonnement que celui décrit pour l'observation. En fait, nous constatons que c'est un double défi; non seulement il faut déterminer lex zones forestières avec pluie, mais aussi les déterminer selon différents seuils de quantité de pluie reliée aux indices. Afin de délimiter des régions de prévisions adaptées à la protection des forêts contre le feu, le Québec a été divisé en quelque 80 zones forestières. Le nombre de zones par région et le nombre de régions formées varient, d'une prévision ou d'une journée à l'autre, selon la complexité des systèmes atmosphériques et selon les besoins de protection particuliers. Pour aider à résoudre le problème des précipitations, nous avons aussi défini des classes de quantités de pluie et avons eu recours aux probabilités.

CLASSES DE QUANTITÉS DE PLUIE (QQ)

Les classes de quantités de pluie (ou gammes de hauteurs de pluie) ont été déterminées en tenant compte des seuils des précipitations qui affectent l'ICL et l'ICD. Ces classes sont exprimées en code et ce sont les suivantes:

CLASSES (codes)	QUANTITÉS (QQ)
00	0,1 mm à 0,5 mm
02	0,6 mm à 2,9 mm
05	3,0 mm à 6,0 mm
10	6,1 mm à 12,0 mm
15	12,1 mm et +

PROBABILITÉS

On distingue deux sortes de probabilités: probabilités d'occurrence de pluie (POP) et probabilités qu'une quantité-seuil de précipitations soit atteinte (PP). La probabilité d'occurrence de pluie (POP) permet au prévisionniste d'exprimer, à l'aide de pourcentage, son appréciation des risques de précipitations ou des "chances" d'avoir de la pluie en un point ou sur une région donnée. Lorsque des précipitations sont prévues, la probabilité (PP) s'interprète comme le pourcentage du territoire qui sera touché par la quantité (QQ) de pluie prévue ou le pourcentage de stations qui observeront la gamme la plus représentative de hauteurs de pluie prévue pour une région. Par exemple, on préfère utiliser la gamme 02 pour la prévision d'averses légères ou de bruine, les gammes 10 ou 15 pour les averses modérées, orages, etc. Une probabilité de 50% d'observer la gamme 05 veut dire que cinq stations sur dix signaleront des précipitations de 3 mm à 6 mm. Mais en pratique, on observe plutôt 50% des stations avec plus de 2,9 mm, tel qu'illustré de la façon suivante:

Classes QQ :00	02	;	05	10	15
Scénarios PP : ..%	..%	;	..%	..%	..%
		'	←-----50%------→		

De toute façon pour la prévision des indices, le problème n'est pas encore résolu puisque nous avons besoin d'une quantité de pluie (P1) pour les sous-routines de calcul et non des probabilités. La méthode utilisée durant les saisons 1967 à 1984, pour évaluer le facteur pluie (P1) pour la prévision des indices, était une méthode subjective basée sur l'expérience et la connaissance des besoins reliés à la détermination des dangers d'incendies.

Afin de réduire la subjectivité de la méthode, tout en rendant le produit utile, nous avons cherché une relation objective entre POP, PP et P1 pour déterminer des scénarios de prévision de pluie.

SCÉNARIOS DE PLUIE

L'idéal aurait été, peut-être, de déterminer pour chacune des gammes des probabilités PP et de calculer par la suite l'espérance mathématique (E) des scénarios, à l'aide de l'équation suivante:
$E(Q_m) - POP \times \sum PP_iQQ_i - P1$. Ainsi on obtiendrait une quantité de pluie P1 qui pourrait être utilisée comme paramètre dans la prévision des indices, lorsque les chances de pluie sont suffisantes. Cependant, l'expérience nous apprend qu'il n'est pas possible de prévoir des probabilités pour chacune des gammes de façon satisfaisante. On peut, par contre, trouver pour une région de protection donnée, les différents scénarios observeés en moyenne selon les POP et les P observées et calculer par la suite les P_1 correspondants.

La figure 3 montre la courbe exponentielle pour la gamme 05, d'après la compilation des données (796 jours) des saison 1978 à 1984 d'une des sept régions du Québec, équipée d'un réseau de vingt-quatre stations. Les P_1 calculés correspondaient, en général, à ceux qu'on utilisait auparavant empiriquement lorsqu'on prévoyait cette gamme. Donc, on a pris cette courbe comme modèle pour trouver les P_1 des autres gammes. Des scénarios de pluie ont été développés au moyen des relations trouvées entre les POP et les PP observés et ont été utilisés pour la prévision automatisée d'indices durant la saisant 1985.

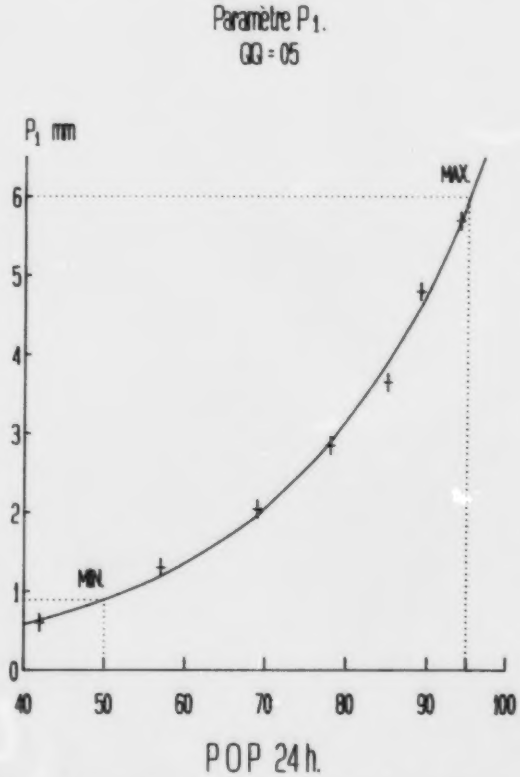


FIG 3. Courbe exponentielle des P1 pour la gamme 05.

On retrouve à la figure 4A les relations entre le POP (0,6 mm) et les PP de 3 mm et 6 mm, donnant des courbes nettement exponentielles (POP≥40), d'après la compilation des données des saisons 1985 à 1988, totalisant près de 2 000 cas ou jours-prévisions. La figure 4B montre les scénarios correspondants pour la gamme 05.

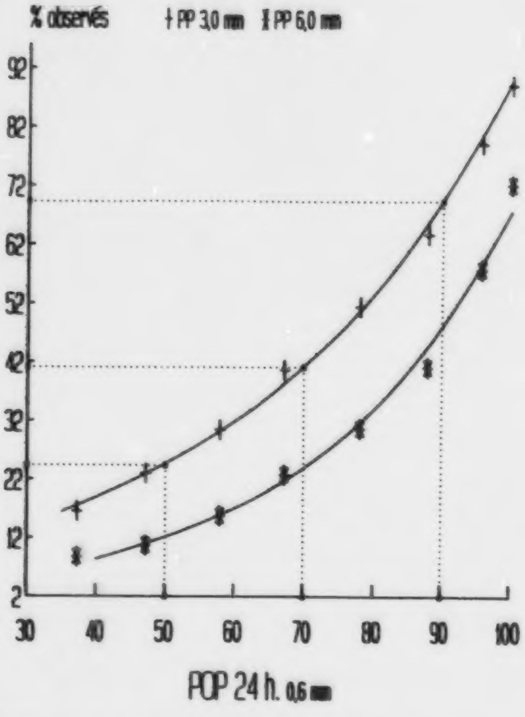


FIG. 4A Relation POP 0,6 mm - PP 3 mm et 6 mm.

POP	QQPP	P1
10	0510	--
20	0510	--
30	0520	--
40	0520	--
50	0530	1.0
60	0530	1.5
70	0540	2.2
80	0550	3.3
85	0560	4.0
90	0570	5.0
95	0580	6.0

FIG. 4B. Scénarios pluie pour la gamme 05.

Nous avons choisi le seuil 0,6 mm pour la probabilité d'occurrence de pluie puisque c'est la hauteur minimum de pluie requise pour affecter l'ICL. Mais, il arrive que les systèmes atmosphériques prévus suggèrent plutôt un seuil de 3 mm ou 6 mm et même davantage comme dans les cas d'orages, de précipitations continues et autres. La figure 5A montre les relations obtenues entre le POP$_{3\ \mathrm{mm}}$ et PP$_{6\ \mathrm{mm}}$ et entre le POP 6 mm et PP 12 mm, soulignant ainsi l'analogie des scénarios observés en moyenne des gammes 05, 10 et 15.

Supposant la même relation du POP (trace) avec la gamme 02, nous obtenons quarante-cinq scénarios de pluie pour la prévision des indices de danger de feu, tel qu'illustré à la figure 5B. Ainsi, on obtient les P1 demandés pour les calculs, en déterminant les POP et les classes de pluie (QQ) les plus représentatives, selon les systèmes atmosphériques en cause, la durée ou l'intensité des précipitations prévues.

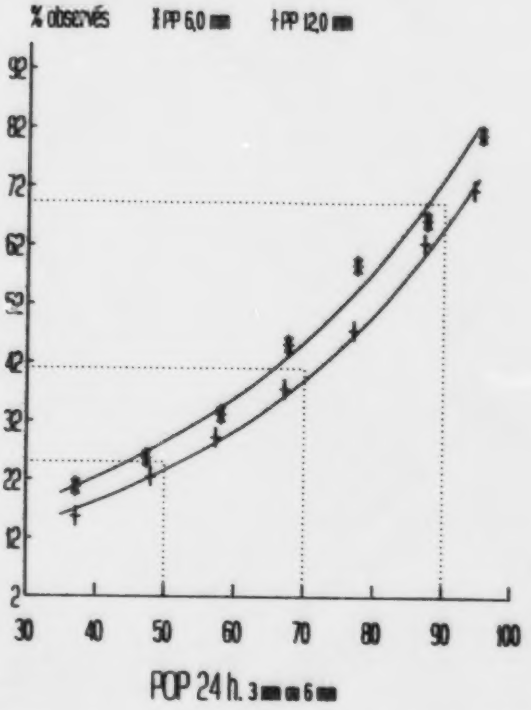


FIG. 5A. POP 3 mm et PP 6 mm POP 6 mm et PP 12 mm.

		QQ			
POP	PP	02	05	10	15
		Paramètre P			
00	00	---	---	---	---
10	10	---	---	---	---
20	10	---	---	---	---
30	20	---	---	---	---
40	20	---	---	---	---
50	30	0.5	1.0	2.0	4.0
60	30	0.7	1.5	3.0	6.0
70	40	1.1	2.2	4.5	9.0
80	50	1.6	3.3	6.5	13.0
85	60	2.0	4.5	8.0	16.0
90	70	2.5	5.0	10.0	20.0
95	80	2.9	6.0	12.0	24.0

FIG. 5B. Scénarios de de pluie pour la gamme pour 00-02-05-10-15.

Cette méthode, en plus d'offrir un moyen très simple et uniforme d'un prévisionniste à l'autre, favorise une meilleure prévision des dangers d'incendie de forêt. Elle permet, en effet, de découper plus finement le territoire forestier en régions de prévision, et d'une façon suffisamment précise pour cerner les zones menacées par des dangers de feux importants et pour discriminer les autres selon les besoins particuliers.

VÉRIFICATION DES PRÉVISIONS

La technique que nous préconisons pour la vérification des prévisions des scénarios de précipitations est celle qui permet d'évaluer et de corriger les erreurs qui affectent les calculs de prévision des indices ICL et ICD employés comme prédicteurs des feux de forêt. Nous avons développé des méthodes qui premettent de vérifier et d'améliorer les algorithmes de prévisions de 12 h, 24 h et 48 h des scénarios de précipitations ainsi que des autres paramètres (humidité relative, température et vent) qui influent sur les calculs d'indices. A titre d'exemple, la figure 6 montre la "fiabilité" des prévisions des POP 24 h par catégorie, illustrant ainsi, d'une façon générale, la précision des scénarios de pluie ou des paramètres P_1.

Les tableaux de la figure 7 montrent la distribution des fréquences obtenues en jours-zones des ICL observés selon les ICL prévus, d'après les scénarios POP 30-40 et 50-60. Ces tableaux permettent d'apprécier la réussite des prévisions de l'ICL à +/-2 unités (87 vérifie les indices 85 à 89). Pour le POP 30-40, même si L'ICL est prévu trop élevé (+20%), l'erreur est bien répartie d'un point de vue pratique pour la prévision de feux de forêt. Par contre, pour les POP 50-60, 62% des P1 prévus proviennent des scénarios de la gamme (QQ) 05 et donnent des dangers trop faibles. Pour une meilleure stratégie, il y aurait lieu de corriger notre algorithme de prévision pour les ICL 83 à 87 en les modifiant pour 85 à 89, tel qu'illustré dans le tableau.

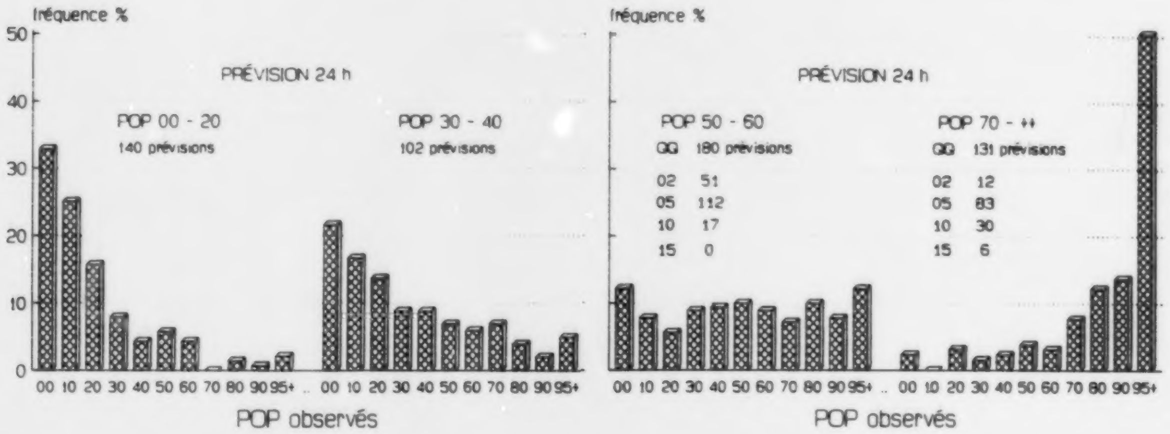
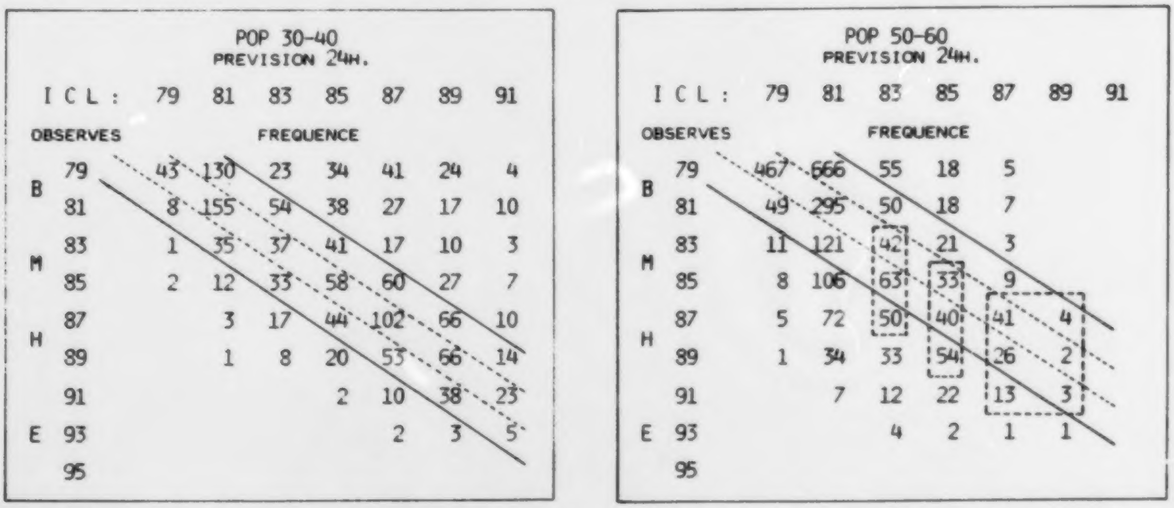


FIG. 6. Distribution des fréquences des POP observés selon les catégories de POP 24 h prévus, du 1er mai au 31 août 1988.



POP 30-40
PREVISION 24H.

	I C L :	79	81	83	85	87	89	91
	OBSERVES				FREQUENCE			
B	79	43	130	23	34	41	24	4
	81	8	155	54	38	27	17	10
M	83	1	35	37	41	17	10	3
	85	2	12	33	58	60	27	7
H	87		3	17	44	102	66	10
	89		1	8	20	53	66	14
	91				2	10	38	23
E	93					2	3	5
	95							

POP 50-60
PREVISION 24H.

	I C L :	79	81	83	85	87	89	91
	OBSERVES				FREQUENCE			
B	79	467	666	55	18	5		
	81	49	295	50	18	7		
M	83	11	121	42	21	3		
	85	8	106	63	33	9		
H	87	5	72	50	40	41	4	
	89	1	34	33	54	26	2	
	91		7	12	22	13	3	
E	93			4	2	1	1	
	95							

FIG. 7. Tableaux de contingence des fréquences en jours-zones de l'ICL, selon les prévisions de 24 h des POP 30-40 et 50-60.

Ouvrages de Référence

TURNER, J.A. et B.D. LAWSON. 1972. La météorologie dans la méthode canadienne d'évaluation des danger d'incendie forestiers. Environnement Canada. Service des forêts. Centre de recherches forestières du Pacifique. Numéro de catalogue: FO42 - 58/1978 F. ISBNO-662-50067-9.

VAN WAGNER, C.E. 1987. Élaboration et structure de la méthode canadienne de l'Indice Forêt-météo. Environnement Canada. Service des forêts. Institut forestier national de Petawawa. Numéro de catalogue 64-35/1987 F. ISBN 0-662-99113-6.

VAN WAGNER, C.E. et T.L. PICKETT. 1985. Équation et programme FORTRAN de l'Indice Forêt-météo de la méthode canadienne. Environnement Canada. Service des forêts. Institut forestier national de Petawawa. Numéro de catalogue F64-33/1985 F. ISBN 0-662-93118-1.

Seasonal Change in Live Fuel Moisture of Understory Plants in Western U.S. Aspen

J. K. BROWN
U.S. Forest Service
Intermountain Research Station
Intermountain Fire Sciences Laboratory
Missoula, Montana

G. D. BOOTH
U.S. Forest Service
Intermountain Research Station
Intermountain Fire Sciences Laboratory
Ogden, Utah

D. G. SIMMERMAN
U.S. Forest Service
Intermountain Research Station
Intermountain Fire Sciences Laboratory
Missoula, Montana

Abstract

Seasonal fluctuation in live fuel moisture content during a wet and dry summer was investigated for several forbs, grasses, and a shrub in aspen forests of Wyoming. Moisture content and its rate of change varied between forbs, grasses, and shrub foliage during the summer. The moisture content of grasses decreased at slow but steady rates. Moisture content of forbs started at about twice that of grasses but was similar by late summer. The patterns of drying for each species were similar between wet and dry seasons, but moisture content remained higher during the wet season. Relationships between live fuel moisture content and the U.S. National Fire Danger Rating System Live Fuel Moisture Model and the Keetch-Byram Drought Index were determined. High variability precluded prediction when data from both seasons were combined. Logistic functions of the seasonal relationships are presented. Moisture contents of vegetation in green and transition stages of curing were similar. Practical aspects of live fuel moisture and degree of curing are discussed for prescribed burning in aspen.

Résumé

Les fluctuations saisonnières de la teneur en humidité du combustible vivant pendant un été caractérisé par des périodes sèches et pluvieuses ont été étudiées chez plusieurs espèces d'herbes non graminéennes et de graminées et chez une espèce d'arbuste de tremblaies dans les forêts du Wyoming. La teneur en humidité du feuillage des herbes non graminéennes, des graminées et de l'arbuste et son taux de modification variaient pendant l'été. La teneur en humidité des herbes non graminéennes diminuait à des laux lents mais réguliers. Au début, la teneur en humidité des espéces d'herbes non graminéennes était approximativement deux fois celle des graminées mais elle était semblable par la fin de l'été. Le régime d'assèchement de chacune des espèces était similaire pendant la saison pluvieuse et la saison sèche, mais la teneur en humidité restait plus élevée pendant la période pluvieuse. Les relations entre la teneur en humidité du combustible vert et le modèle d'humidité du combustible vert du système américain d'évaluation du danger d'incendie et l'indice de sécheresse Keetch-Byram ont été établies. La forte variabilité a empêché de faire des prévisions lorsque les données des deux saisons étaient combinées. Les fonctions logistiques des relations saisonnières sont présentées. Les teneurs en eau de la végétation à l'état vert et en cours d'assèchement étaient similaires. Les aspects pratiques de la teneur en humidité du combustible vert et du degré d'assèchement sont examinées en fonction du brûlage dirigé dans une tremblaie.

Introduction

Flammability of aspen stands depends largely on condition of live understory vegetation. Live herbaceous plants and shrubs are the primary fuel supporting spread of fire in aspen. The aspen forest generally

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

is considered as difficult to burn because of the prominence of live fuels and often sparse distribution of fine dead fuels. However, many aspen stands become flammable when live vegetation cures enough to contribute to fire spread rather than hinder it. Prescribed burning then may be possible.

Live fuels act as a heat sink. As curing progresses, the percentage of moisture content of living tissues is reduced and some plant parts die. At some point these fuels can be adequately preheated to ignite within the flaming front and contribute to fire spread. Degree of curing is probably the most important variable to monitor for determining when prescribed fires can be successfully conducted in aspen forests. This paper reports on a study of live fuel moisture trends, predictability of live fuel moisture content, and practical aspects of determining curing.

Seasonal fluctuation in percentage of moisture content has been investigated for a number of tree and shrub species (Olson 1980, Blackmarr and Flanner 1968, Johnson 1966, Philpot 1963, Reifsnyder 1961). Leaf water content varied considerably early in the growing season but tended to converge around 100 to 130% late in the growing season. In the West, seasonal trends in herbaceous plant moisture content have received only limited study (Richards 1940, Olson 1980). In the Lake States, moisture content of a number of herbaceous species varied considerably and had less seasonal change than reported for western species (Loomis and Blank 1981, Loomis et al. 1979).

Prediction of percentage of moisture content from seasonal drying indices has met with varied success. Correspondence between actual moisture content and the National Fire Danger Rating System Live Fuel Moisture Model (NFDRS) was poor for Lake States herbaceous species (Loomis and Blank 1981). Olson (1980) reported reasonably good relationships between moisture content and the Keetch-Byram Drought Index (KBDI) for foliage of several shrubs and a perennial grass. Efforts to predict live fuel moisture content from these indices have been based on a limited range of seasonal drying conditions.

The response of live fuel moisture content to environmental stress is poorly understood. Plant physiologists have studied water relations more in terms of stress or water pressure potential than water content. Seasonal fluctuations are more closely related to growth and maturation of the leaf than to stress (Striffler and Oldaker 1979). Leaves of woody species have high moisture content when they are new and succulent. As dry matter increases, percentage of moisture content decreases even though water content stays about the same. Phenological changes in plant processes appear to have more effect on moisture content than does environmental stress.

Methods

Field sampling was conducted during the summers of 1981 and 1982 on the Bridger-Teton National Forest, Wyoming, in aspen forest at 2440 m elevation. Moisture content was sampled for four forb species, coneflower (Rudbeckia occidentalis), sticky geranium (Geranium viscosissimum), mule's ear (Wyethia amplexicaulis), and cutleaf balsamroot (Balsamorhiza macrophylla); a shrub, buffaloberry (Sherpherdia canadensis); and a mixture of perennial grass species, mostly California brome (Bromus carinatus), blue wild rye (Elymus glaucus), and slender wheatgrass (Agropyron trachycaulum). Samples of coneflower, geranium, and grasses were taken from two adjacent aspen stands having open and closed crown canopies. Both stands were in the Populus tremuloides/Rudbeckia community type (Youngblood and Mueggler 1981). The other species were sampled in a nearby mixed aspen and conifer stand characterized as a P. tremuloides-Abies lasiocarpa/Berberis repens community type.

Duplicate samples of each species were collected weekly during midafternoon. Two, 10-cm diameter soil cans were used to collect the samples at four points separated by 3 m along randomly oriented transects in each stand. Leaves and stalks of herbaceous species were collected by spiraling away from the sample point until approximately half of a container was filled, then moving to the next sample point. Current year growth was collected that combined plant tissues at various stages of curing. For buffaloberry, foliage and stem material less that 0.6 cm diameter of buffaloberry were collected separately from at least four plants. Samples were weighed, oven dried for 10 hours at 100°C, and reweighed. Moisture contents were calculated as percentage of oven dry weights.

Temperatures and rainfall were recorded during the field season at the sample sites. The NFDRS (Burgan 1979) and KBDI (Keetch and Byram 1968) were computed from these observations and from nearby weather station observations to establish early growing season values. The NFDRS climate class 3, a mechanism for adjusting to regional drying rates, was assumed. During the green stage, drying is a function of precipitation and temperature. The KDBI is also calculated from precipitation and daily maximum temperature. It represents the net effect of evapotranspiration and precipitation in producing cumulative moisture deficiency in deep duff or upper soil layers.

The moisture content was related to time of season by fitting the logistic function:

$$\text{Percentage of moisture} = \frac{D}{[1 + A \exp(B(\text{Day of year} - 196))]}$$

where A, B, and D = parameters of logistic function

To develop color criteria for field separation of plant tissue into similar moisture content categories, additional moisture samples were collected for coneflower, mule's ear, and grasses in 1982. Plant tissues were collected at several points along a transect and carefully separated into green, transition, and cured components. Plant tissues in transition were typically yellowish, having lost most of the green coloration of

Table 1. Results from fitting logistic functions to percentage of moisture content using day of year as the independent variable.

Species	Year	Estimates of logistic parameters A Alpha	 B Beta	 D Delta	R^{2*a}
Coneflower	1981	0.0737	0.0563	399.3	0.979
	1982	0.3912	0.0312	694.1	0.988
Sticky geranium	1981	0.0176	0.0574	318.6	0.750
	1982	0.6869	0.0199	726.2	0.962
Mule's ear and cutleaf balsam combined	1981	0.0018	0.1091	315.6	0.871
	1982	0.0618	0.0585	498.7	0.983
Buffaloberry	1981	0.0293	0.0341	198.9	0.344
	1982	1.0000[b]	0.0110	535.9	0.745
Perenial grasses	1981	1.0000[b]	0.0150	308.9	0.517
	1982	1.0000[b]	0.0207	470.5	0.887

[a] Due to the nonlinear nature of the logistic function, the usual R^2 is not applicable, but we have included what we denote by R^{2*} which is defined as:

$$R^{2*} = 1 - \text{Uncorrected Residual SS} / \text{Corrected Total SS}$$

This value, like R^2, lies between zero and one. However, it is generally higher than R^2 and does not have an equivalent interpretation. Nevertheless, high values, say greater than 0.950, reflect a tight fit.

[b] The upper bound of 1.0 was reached during fitting. The fit is unstable.

Table 2. Precipitation amounts (cm) from two official weather stations (Kemmerer and Fontenelle Dam, WY) and at the study site.

Month	Kemmerer 1981	 1982	Fontenelle 1981	 1982	Study Site 1981	 1982
June	0.38	1.27	0.15	0.99	--	--
July	1.90	5.16	1.65	6.10	--	--
August	0.33	3.15	0.18	0.58	1.09	1.83
September	0.94	11.63	1.32	13.31	2.01	9.85
Total	3.55	21.21	3.30	20.98	3.10	11.68

the green stage. Cured leaf tissue showed brown coloration rather than yellow. Cured grass stalks remained straw colored, but the yellow was largely washed out.

Results

SEASONAL FLUCTUATIONS

Moisture content decreased seasonally in the typical manner but varied considerably between 1981, a dry summer, and 1982, a wet summer (Figure 1). Table 1 shows the results of fitting the logistic functions in Figure 1. Data for balsamroot and mule's ear were combined because their moisture contents were similar. Differences in moisture content between 1981 and 1982 ranged from about 20 to 100% for the different species and dates during the growing season. Precipitation during the growing season at the official weather stations was six times greater in 1982 than in 1981 (Table 2). At the study site during August and September, precipitation was nearly four times greater in 1982 than in 1981.

During the wet and dry summers, grasses cured at slow but steady rates beginning early in the growing season, primarily because seed stalks cured early even though leaves remained lush (Figure 1). Buffaloberry also cured at slow steady rates. Moisture content of the forbs started at about twice that of grasses but was similar by late summer. During the dry summer, forb moisture content decreased slowly early in the season, then drying rates accelerated. During the wet summer, forb moisture content began at higher values and decreased at steadier rates compared to the dry summer. The rate of change in moisture content for the curves in Figure 1 can be easily seen in Figure 2. The rates of change were always less than 0 because moisture content was always decreasing, thus indicating drying. Patterns of drying rate were reasonably consistent among the species. A pronounced change in drying rate occurred for balsamroot and mule's ear, but only a modest change in drying rate was observed for geranium. Changes in drying rates for grass and buffaloberry were slight. The dates of most rapid drying among forbs, shown by the lowest point on the curves, occurred earlier in the wet year than in the dry year.

Differences in moisture content between green and transition stage vegetation were relatively small, especially for forbs (Figure 3). The moisture content of the transition stage decreased for forbs as the summer progressed but remained essentially the same at about 100% for grasses. Some additional observations on moisture content of herbaceous vegetation were:

1. Stalk and leaf moisture contents of coneflower, a tall, rank forb, were similar throughout the growing season.
2. Rainfall of about 6 mm or more prompted an increase in moisture content of both forbs and grasses during July and August. However, at some point in September, the drying trend of forbs became entrenched. After that, rainfall did not stall the curing process. The perennial grasses responded to rainfall in late September and early October by a greenup of basal leaves and an increase in moisture content.
3. Herbaceous vegetation cured more rapidly under the open canopied stand especially during the dry summer of 1981. For example, moisture content of grasses averaged 41 percentage points higher in the closed stand than in the adjacent open stand. In curing time, moisture contents in the closed stand were 2 to 3 weeks behind those in the open stand.

Moisture content of buffaloberry foliage decreased at a nearly steady rate similar to the grasses but at a higher moisture level. Moisture content varied from 130 to 280%, similar to the range reported for willow (*Salix spp.*), snowbrush (*Ceanothus velutinus*) and ninebark (*Physocarpus malvaceous*), which are also Rocky Mountain forest shrub species (Richards 1940). Moisture content remained in excess of 120% until the leaves changed to a brownish color just before falling from the stems in autumn. Stemwood moisture content, sampled in 1981, ranged from 85 to 110% throughout the growing season.

DRYING INDICES

Moisture content of grasses corresponded reasonably well to the NFDRS during mid to late summer (Figure 4). However, forb moisture content, represented by coneflower, related poorly to the NFDRS. A similarly poor relationship was also observed by Loomis and Blank (1981). The NFDRS was not plotted after early September because the vegetation was no longer in the green stage. Forbs fluctuated through a much greater range in moisture content than allowed by the NFDRS Live Fuel Moisture Model, which restricts the maximum herbaceous fuel moisture content to 250%.

During the prolonged sustained drying period in 1981, the KBDI related well inversely to herbaceous moisture contents (Figure 4). Regression relationships between percentage of moisture content (MC) and KBDI for the species in Figure 4, 1981, are:

$$\text{Coneflower MC} = 543 \ -1.480\ (\text{KDBI}),\ R^2 = 0.92,\ Sy.x = 38$$

$$\text{Grass MC} = 190 \ -0.362\ (\text{KDBI}),\ R^2 = 0.57,\ Sy.x = 28$$

where Sy.x is residual standard error.

However, correlations between KDBI and forb moistures fell apart in late summer and early fall when the physiological process of curing was entrenched regardless of soil moisture. Forb moisture content decreased even following rainfall. However, the correlation for perennial grasses late in the season remained good because plant moisture content increased following rainfall. During the wet summer of 1982, KBDI related poorly to herbaceous plant moisture content. If data from both summers were combined the correlation would remain poor (Figure 4). Use of KBDI to predict herbaceous plant moisture

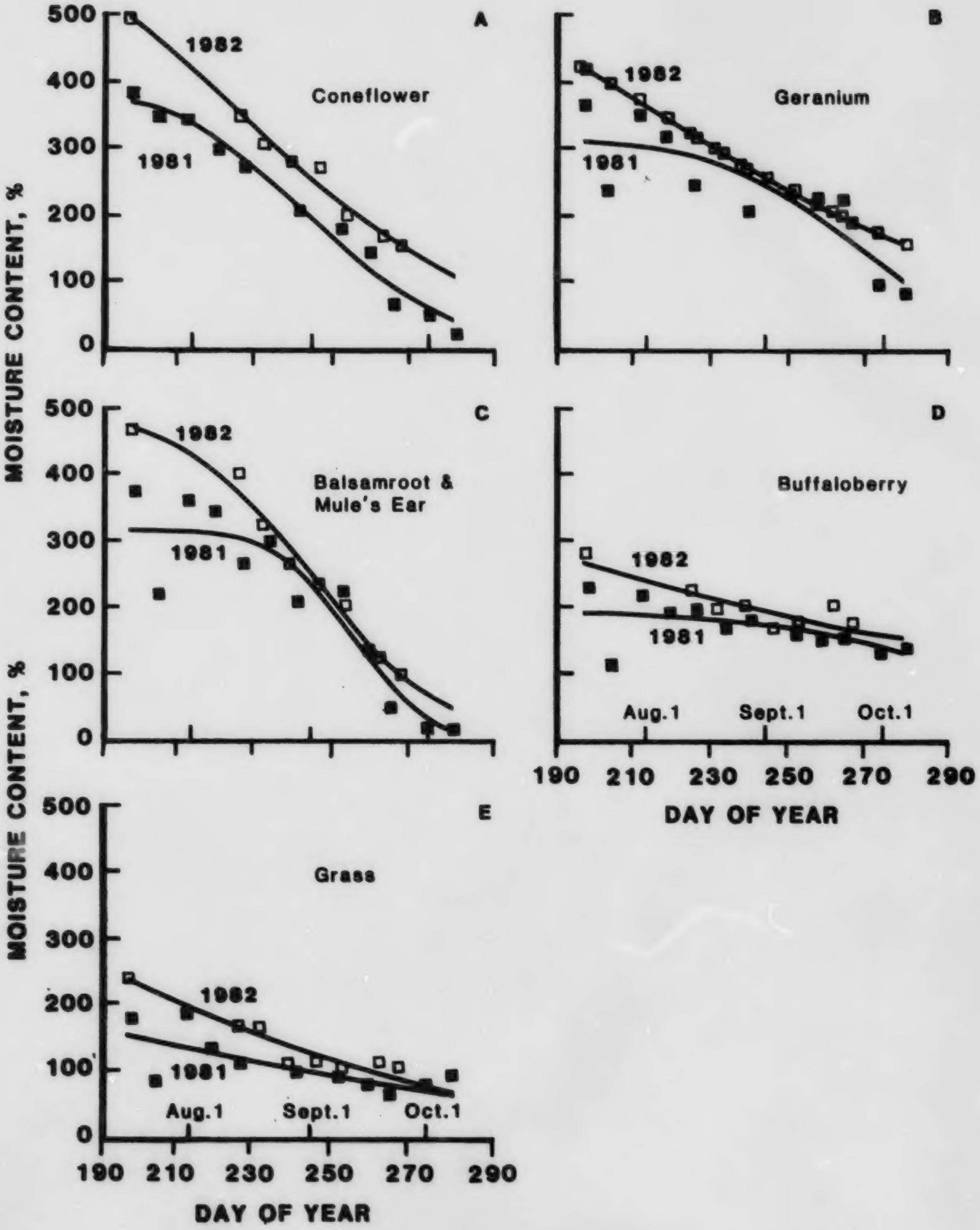


FIG. 1. Seasonal change in moisture content for coneflower, geranium, balsamroot and mule's ear, grasses, and buffaloberry.

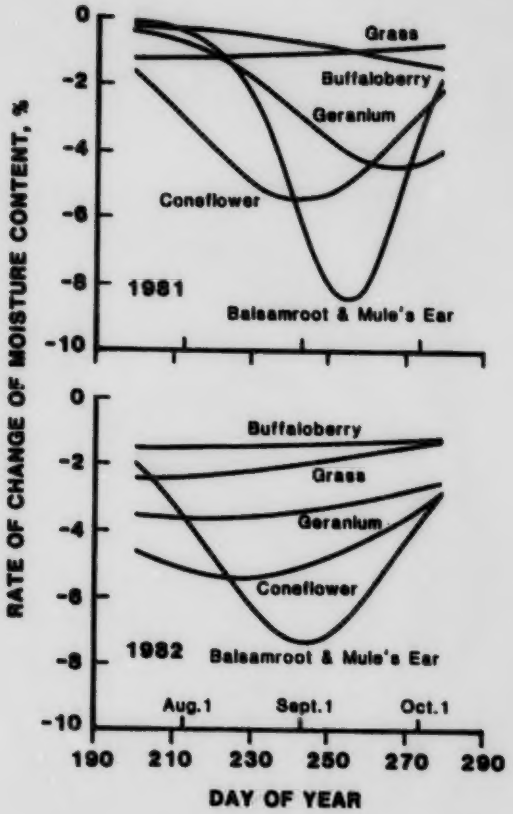


FIG. 2. Slopes of the seasonal moisture logistic functions (table 1) plotted through the 1981 and 1982 seasons to illustrate changes in curing rate.

content appears reasonable during continuous drying periods but not during summers with significant precipitation.

APPLICATION

To estimate percentage of moisture content of live fuels, especially herbaceous plants, time of year is the simplest and probably the most accurate and reliable indicator. Seasonal drying relationships (Table 1 or Figure 1) can be used to estimate this percentage. The NFDRS and KBDI appear inconsistent as predictors of moisture content. The NFDRS was designed to estimate relative flammability trends seasonally. It may function adequately for this purpose but does not appear helpful for prescribed burning.

For prescribed burning, the most meaningful measure of flammability related to herbaceous vegetation is degree of curing, which indicates the amount of dead herbaceous material at potentially low moisture content. In aspen forests where herbaceous vegetation is the primary fine fuel, at least 50% curing is needed to sustain fire spread. In stands containing substantial conifers, less than 50% curing may be sufficient to sustain fire spread. In these stands, other fine fuels such as fallen needles, leaves, and twigs and dead shrub stemwood contribute significantly to fire spread. The degree of curing required for successful prescribed burning needs substantiation. Procedures for estimating percentage of curing accompanied by color photographs are discussed by Brown and Simmerman (1986). To estimate curing, green and transition stage vegetation can be considered the same.

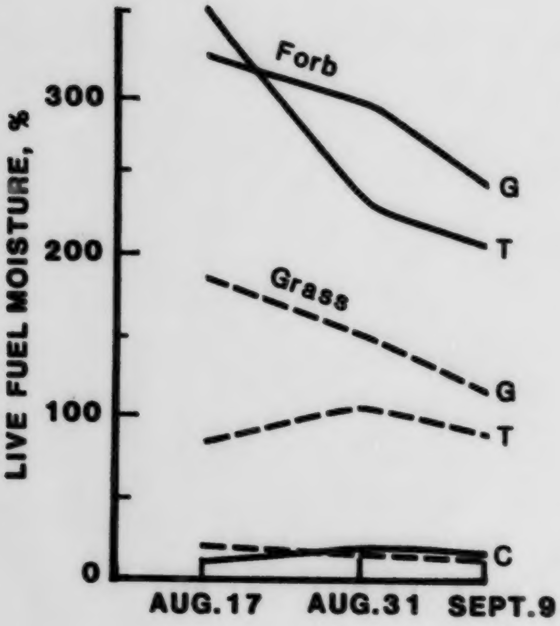


FIG. 3. Moisture content of forbs (mule's ear and coneflower) and grasses on three dates in 1982. The plant tissues were separated into green (G), transition (T), and cured (C) components based on color and texture.

This study showed that live fuel moisture contents vary greatly between some species and throughout the growing season. However, they can be estimated well enough to determine when to ignite prescribed fires.

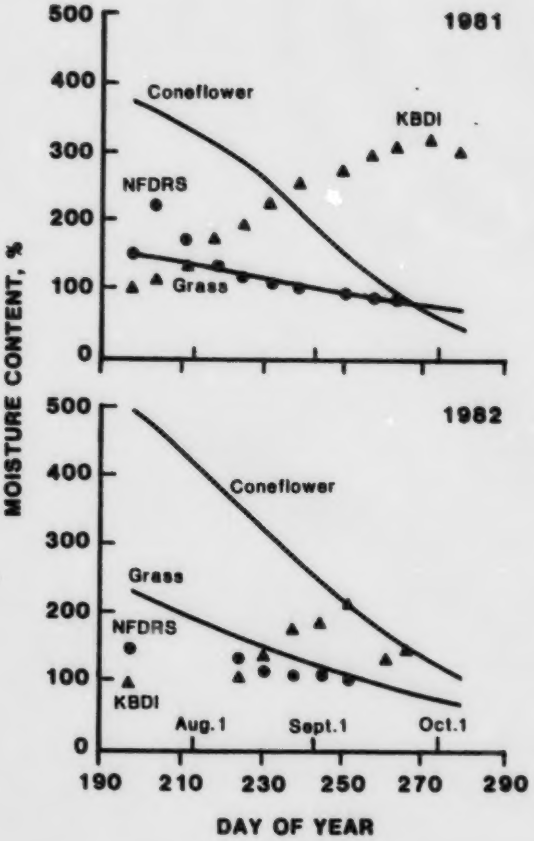


FIG. 4. Moisture contents of coneflower, grasses, and NFDRS and the KBDI plotted for 1981 and 1982.

References

BLACKMARR, W.H., and W.B. FLANNER. 1968. Seasonal and diurnal variation in moisture content of six species of Pocosin shrubs. USDA For. Serv. Res. Pap. SE-33, Southeastern For. Exp. Sta.

BROWN, J.K., and D.G. SIMMERMAN. 1986. Appraising fuels and flammability in western aspen: A prescribed fire guide. USDA For. Serv. Gen. Tech. Rep. INT-205, Intermt. Res. Sta.

BURGAN, R.E. 1979. Estimating live fuel moisture for the 1978 National Fire Danger Rating System. USDA For. Serv. Res. Pap. INT-226. Intermt. For. and Range Exp. Sta.

JOHNSON, V.J. 1966. Seasonal fluctuations in moisture content in pine foliage. USDA For. Serv. Res. Note. NC-11. North Central For. Exp. Sta.

KEETCH, J.J., and G.M. BYRAM. 1968. A drought index for forest fire control. USDA For. Serv. Res. Pap. SE-38. Southeastern For. Exp. Sta.

LOOMIS, R.M., and R.R. BLANK. 1981. Summer moisture content of some northern lower Michigan understory plants. USDA For. Serv. Res. Note NC-263, North Central For. Exp. Sta.

LOOMIS, R.M., P.J. ROUSSOPOULOS, and R.W. BLANK. 1979. Summer moisture contents of understory vegetation in northeastern Minnerota. USDA For. Serv. Res. Pap. NC-179, North Central For. Exp. Sta.

OLSON, C.M. 1980. An evaluation of the Keetch-Byran drought index as a predictor of foliar moisture content in a chaparral community. Proc. Sixth Conf. Fire and For. Meteor., Seattle, WA., Apr. 22-24, 1980, Soc. Amer. For., Bethesda, MD. Pp. 241-244.

PHILPOT, C.W. 1963. The moisture content of ponderosa pine and white leaf manfanite foliage in the Central Sierra Nevada. USDA For. Serv. Res. Note PSW-39. Pacific Southwest For. and Range Exp. Sta.

REIFSNYDER, W.E. 1961. Seasonal variations in moisture content of green leaves of mountain laurel. For. Sci. 7(1): 16-23.

RICHARDS, L.W. 1940. Effects of certain chemical attributes of vegetation on forest inflammability. J. Agr. Res. 60: 833-838.

STRIFFLER, W.D. and P. OLDAKER. 1979. A live fuel moisture prediction model. Project completion report contract No. 16-543-CA. USDA For. Serv., Rocky Mountain For. and Range Exp. Sta.

YOUNGBLOOD, A.P., and W.F. MUEGGLER. 1981. Aspen community types on the Bridger-Teton National Forest in western Wyoming. USDA For. Serv. Res. Pap. INT-272, Intermt. For. and Range Exp. Sta.

Heating-Related Water Transport in Woody Plants: Summary of Experimental Results

W. B. COHEN AND P. N. OMI
Colorado State University
Fort Collins, Colorado

R. C. ROTHERMEL
Intermountain Fire Sciences Laboratory
Missoula, Montana

Abstract

We present a summary of results designed to test a hypothesis relating drought to crown fire in woody plants. The hypothesis suggests that nondrought-stressed plants have the capability of transporting water to heated foliated branches, but that stressed plants do not. The experiments indicate that water is transported from unheated woody stems to heated foliated branches of a number of species, and that drought influences the amount of heating-related transport. Methods for calculating energy required to ignite live vegetation must account for water transported to the heated plant material. A physiological measure of water stress in combination with water content should provide better energy estimates than either alone.

Résumé

Nous présentons un sommaire des résultats élaborés afin d'évaluer une hypothèse qui relie la sécheresse au feu de cime dans les plantes ligneuses. L'hypothèse suggère que les plantes non-affectées par la sécheresse ont la capacité de transporter l'eau à ses branches feuillées sous l'action de la chaleur, mais que les plantes qui sont affectées par la sécheresse n'ont pas cette capacité. Les expériences indiquent que l'eau est transportée des branches ligneuses coupées qui ne sont pas sous l'action de la chaleur aux branches feuillées sous l'action de la chaleur de plusieurs espèces. La sécheresse influence le montant transporté par la chaleur. Les méthodes qui calculent l'énergie nécessaire pour allumer la végétation à l'état vert doivent tenir compte de l'eau transportée à la matière des plantes sous l'action de la chaleur. Une mesure physiologique du montant de l'eau affectée, encomsinaison avec le contenu de l'eau deviait fournir des meilleures estimations que chacun de ceux-ci seues.

Introduction

Attempts to explain the increased propensity of woody plants to ignite during periods of drought led to the hypothesis that a heating-related water transport mechanism may provide a natural resistance to fire that does not operate when plants are drought-stressed (Rothermel and Susott, in preparation). The hypothesis was first introduced and examined experimentally by Cohen and others (1987), and then followed by more in-depth examinations using a specially designed tree branch calorimeter in two separate experiments. Cohen and others (submitted) describe the first calorimeter experiment in detail and Cohen and Omi (in preparation) describe the second. This paper summarizes the three heating experiments.

Summary of Results

Cohen and others (1987) attached severed branches of three conifer species (Pinus contorta, Picea engelmannii, and Abies lasiocarpa) to potometers that supplied unlimited amounts of water on demand and permitted the monitoring of branch water uptake. After measuring branch uptake/transpiration rates prior to heating, the branches were heated to 225°C in an oven. Relative to water uptake rates prior to heating, uptake by branches of all three species increased dramatically after one minute of heating. Branches of P. contorta, P. engelmannii, and A. lasiocarpa exhibited mean maximum uptake rates of 50, 13, and 5 times greater, respectively, than their transpiration rates prior to heating. Maximum uptake rates were attained within 5 to 7 minutes of heating, after the branch foliage was already brown. Once the foliage became brittle, water uptake rates declined slowly. After twenty minutes of heating, and long after the foliage became brittle, the woody stems remained pliable and the branches still drew water from the potometers at rates about one-half of the maximum. These results support the heating-related water transport hypothesis

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

and provided impetus for further study--this time, using the calorimeter.

The calorimeter measures the energy environment surrounding a branch inside its heating chamber. The amount of energy absorbed by the branch is primarily a function of the amount of water vaporized from it. Calorimeter operation and procedures for calculating energy absorbed by, and water vaporized from, individual branches are described in detail by Cohen and others (submitted).

For the first calorimeter experiment, matched branch tip pairs were selected from nondrought-stressed P. contorta trees. Each matched pair came from the same lateral branch and lateral branches were selected from several different trees. One tip from each pair was heated after first detaching it from the lateral branch, while the other was heated intact to the parent plant. Rationale for heating matched branch pairs in this manner is as follows. If water is transported from unheated stems into the foliated tips of intact heated branches, more water should be vaporized per gram of dry heated fuel from intact tips during an extended heating period, than from similar, but detached tips during an equivalent heating period.

When heated from ambient temperature to 250°C (at a 15°C min^{-1} temperature increase rate) in the calorimeter, intact P. contorta branches absorbed a mean of 49 % more energy than detached branches (cumulative absorption difference, CAD). This is equivalent to 0.62 grams of water per gram of dry fuel. After heating, no water remained in the detached branches and intact branches had a mean residual water content (ResWC) of 10.8 %. Water vaporization from intact branches was 20 times more during heating, than the amount associated with normal transpiration. These results further support the hypothesis by demonstrating that water transported to intact conifer branches is vaporized from them during heating.

The objective of the second calorimeter experiment was twofold: 1) to examine whether other woody plant species are capable of transporting water to heated branches; and 2) to evaluate the relationship between temporal changes in drought, plant water stress, and heating-related water transport. Experiments were conducted on three plant species native to southern California, one conifer (Pinus coulteri), and two chaparral (Ceanothus crassifolius and Salvia mellifera). For each species, one set of matched pair branch heatings occurred at three separate times of the year (temporal sets, TSs). With a few exceptions, each TS of heatings was conducted in a similar manner as in the first calorimeter experiment. Differences between the two experiments are described in detail by Cohen and Omi (in preparation).

The first TS of heatings for the second calorimeter experiment occurred in early spring, when rainfall was plentiful by local standards. Rainfall was considerably less in volume leading up to the second TS of heatings, that took place in late spring, than during the time leading up to TS 1. Just after the completion of all TS 2 heatings, rainfall ceased and the annual recurrence of drought began. The third TS of heatings were conducted in summer, after a period of about three or four months (depending on species heated) without substantial rainfall.

Results of the first TS of branch heatings during the second calorimeter experiment, under nondrought conditions, indicate that the pine and both chaparral species are capable of transporting water to heated foliated branches. The mean CAD for P. coulteri branches of the first TS was 576 J g^{-1}. This equates to 0.23 grams more water per gram of dry fuel vaporized from intact than from detached branches. The calorimeter is too "noisy" to provide useful energy data for the relatively small size branches of the chaparral species. Thus, for the chaparral, ResWC data were examined for evidence of heating-related water transport. For C. crassifolius and S. mellifera, mean differences in ResWC (ResWCD, intact minus detached) were 4.6 and 7.3 %, respectively. These results indicate the chaparral species also appear to have the capability to transport water to heated foliated branches.

Results of the second and third TSs of heatings from the second calorimeter experiment suggest that a strong relationship exists between time of year heating occurred (and therefore amount of rainfall, or level of drought) and the amount of heating-related water transport. Again, the CAD data for the pine species and the ResWC data for the two chaparral species were examined for evidence. Mean CAD at the end of heating for the second TS of P. coulteri was slightly less than for the first TS (480 J g^{-1} of dry heated fuel). The third TS of branch heatings for this species yielded a mean CAD of -71 J g^{-1}. Mean ResWCDs for C. crassifolius TSs 2 and 3 were 4.1 and 0.6 %, respectively. For S. mellifera the differences were 3.8 and 0.7 %.

Water stress measurements for both chaparral species also reflected the seasonal changes in drought. Stress levels in these species were low for the first two TSs of heatings and relatively high for the third TS. Water stress measurements for P. coulteri were low for all three heating sets. Thus, seasonal changes in water stress did not track changes in drought for this species. Soil moisture, phenological state, or water content of the tree bowl may be more important for estimating the amount of heating-related water transport in pine species.

In the second calorimeter experiment, three measures of plant water stress were examined, water content (WC), relative water content (RWC), and water potential (Ψ). For S. mellifera, all three measures of stress were highly correlated with each other and with temporal changes in heating-related water transport. For C. crassifolius, RWC and Ψ were highly correlated with each other and with water transport, while WC was not. None of the stress measures were well correlated with each other or with amount of water transport in P. coulteri. Of the three however, Ψ was most closely related to the amount of water transport.

Thus, among species, Ψ seems the best correlated with heating-related water transport.

Conclusions

Several species of woody plants have the ability to transport water to foliated branches that are heated. Furthermore, drought has the effect of diminishing the amount of heating-related water transport. Implications are that methods of calculating energy required for ignition of live plants can not be based simply on the amount of water contained in the heated material, as it is for dead plant material. Instead, the energy calculation must account for water transported to the heated plant material and released to the air during heating.

Plant water stress can be measured in several ways. Of the three measures of stress examined for their relationship with heating-related water transport and drought, water content is least correlated with both. Which physiologic stress measure (relative water content or water potential) will best estimate amount of transport may depend on species. Overall however, water potential appears most strongly correlated with the amount of heating-related water transport among species. Water content and a physiologic measure of stress may be best used together for modeling the amount of energy absorption by heated woody plant crowns.

References

COHEN, W.B., P.N. OMI, AND M.R. KAUFMANN. 1987. Water uptake of subalpine conifer branches during heating. In Proc., Tech. Conf., Management of Subalpine Forests: Building on 50 Years of Research, p. 207-210. USDA, For. Serv., Gen. Tech. Rep. RM-149, Rocky Mountain Forest and Range Experiment Station, Ft. Collins, CO.

COHEN, W.B., P.N. OMI, AND M.R. KAUFMANN. (Submitted). Water transport to heated intact lodgepole pine branches. For. Sci.

COHEN, W.B. AND P.N. OMI. (In preparation). Drought and heating-related water transport in woody plants.

ROTHERMEL, R.C. AND R.A. SUSOTT. (In preparation). Natural resistance of conifer trees to crown fire due to accelerated water transport: a hypothesis.

Analysis of the Fire Behavior Associated with Three 1988 Spring Wild Fires in Central Canada

K. G. HIRSCH
Forestry Canada, Northwest Region
Winnipeg, Manitoba

Abstract

Between April 30 and May 2, 1988 extreme fire behavior was exhibited by the Gull Lake and Brereton Lake wildfires in southeastern Manitoba and the Kenora #14/88 conflagration in northwestern Ontario. A strong upper ridge centered over northern Ontario blocked the movement of a very moist air mass approximately 120 km west of the fire areas. Open wind speeds during peak burning conditions averaged between 25 km/h and 50 km/h, with maximum gusts near 80 km/h. Five major fire runs in mature and immature jack pine stands were documented. The calculated values of the Canadian Forest Fire Behavior Prediction System compared favorably (±25%) to the actual head fire spread rates, which ranged from 0.8 km/h to 3.5 km/h.

Résumé

Entre le 30 avril et le 2 mai 1988 des comportements extrêmes du feu se sont produits piès des feux de friches du Lac Gull et du Lac Brereton 1988, au sud-est du Manitoba et la conflagration #14188 à Kenora au nord- ouest de l'Ontario. Une forte crête de haute pression centrée au-dessus du nord de l'Ontario a bloqué le déplacement d'un système d'air très humide à environ 120 km à l'ouest des régions où des incendies rageaient. Au cours de cette période où les conditions de brûlage étaient les meilleures la vitesse moyenne des vents oscillait entre 25 et 50 km/h, des rafales maximales de près de 80 km/h ayant été enregistrées. Cinq aggravations majeures de feu dans des peuplements de pins quis arrivés et pas encore arrivés à maturité ont été documentées. Les valeurs calculées à l'aide de la Méthode cnadienne de prévision du comportement des incendies de forêt (PCI) se sont comparées favarablement (±25%) aux taux actuels de propagation du feu sous le vent, qui se situaient entre 0.8 km/h à 3.5 km/h.

Introduction

The occurrence of wildfires prior to spring leaf-flush is a perennial problem in some areas of southeastern Manitoba and northwestern Ontario. In most instances these fires remain relatively small; however, occasionally large fires do occur. For example, of the over 800 fires that occurred prior to or during the month of May in southeastern Manitoba from 1976-86, 72% were less than 10 ha in size. The remaining 28% of the fires burned 138,000 ha of forested land or 99.3% of the region's total area burned during these months. Also significant is the fact that nearly 90% of all these fires were man-caused.

The primary values at risk in this area include rural homes, summer cottage developments, outdoor recreational areas, and forestry values. Because of this, wildfire suppression is a high priority in this region for both the Ontario Ministry of Natural Resources (OMNR) and Manitoba Natural Resources (MNR). One source of information that fire managers in this area and across Canada have increasingly used in their suppression operations is the Canadian Forest Fire Behavior Prediction (FBP) System[1] (Lawson et al. 1985). This system predicts fire behavior in specific fuel types for different weather conditions and topographic features. It has been utilized for pre-suppression planning, initial attack dispatch and both agencies have found it effective in project fire situations (Stocks and Flannigan 1987, Hirsch 1988a). It is based on over 400 experimental fires and well-documented wildfires, however, the need for additional information at the extreme end of the fire behavior scale still exists in order to verify or refine the FBP System (Alexander and Lanoville 1987). An effective

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

way to meet this need is to gather information from large wildfires through formal documentation. A large number of case studies have been published for wildfires in northwestern Ontario (e.g., Stocks and Walker 1973, Stocks 1975, Street and Stocks 1983, Stocks and Flannigan 1987), Canada, and abroad[2] but none have been completed for any forest fires in Manitoba. In light of these factors, the purpose of this paper is to: (a) describe the fire weather conditions which contributed to the occurrence of extreme fire behavior on the Gull Lake and Brereton Lake Fires in southeastern Manitoba and the Kenora #14/88 Fire in northwestern Ontario, and (b) present a retrospective comparison of those values calculated by the FBP System with the actual fire behavior on each of these wildfires.

The Wildfire Chronologies

GULL LAKE FIRE

The Gull Lake Fire was detected and reported at 1430 Central Daylight Time (CDT) on May 1, 1988. The fire area was located approximately 60 km northeast of the city of Winnipeg (Figs. 1 and 2). Initially, this man-caused fire was burning in a grass field but by 1532 CDT strong southerly winds had pushed it northward to the edge of a long, narrow stand of 30-40 year old jack pine (Pinus banksiana). Because of the fire's intensity, direct ground attack was not possible and though airtanker support was requested, it was denied due to the high winds in Winnipeg which grounded the CL-215 skimmer aircraft. Indirect attack with bulldozers was attempted but proved to be hazardous for the operators. At 1628 CDT the head fire was reported to be under the hydro-electric power lines approximately 3.0 km north of where it entered the stand of jack pine. It continued to spread in a northerly direction placing a large number of rural homes and cottages at Gull Lake in jeopardy. By 1730 CDT the head fire had travelled 6.4 km and was approaching a large gravel pit. Concern was expressed that if the fire was not stopped at this point it could jump northwestward over Highway 59 and spread through unlimited fuels towards the highly populated recreational area of Victoria Beach. Around 1900 CDT the fire's flank did actually jump the highway, but it spread into a wet, treed-bog area that slowed its progress considerably. Backburning to ensure no further fire spread began at 1950 CDT; however, only five minutes later the wildfire virtually stopped due to a dramatic change in the weather.

On May 2, a full-scale suppression effort was undertaken and the few hotspots that did develop were suppressed with little difficulty. There was no further increase in the fire's size after May 2, resulting in a final area burned of 1620 ha.

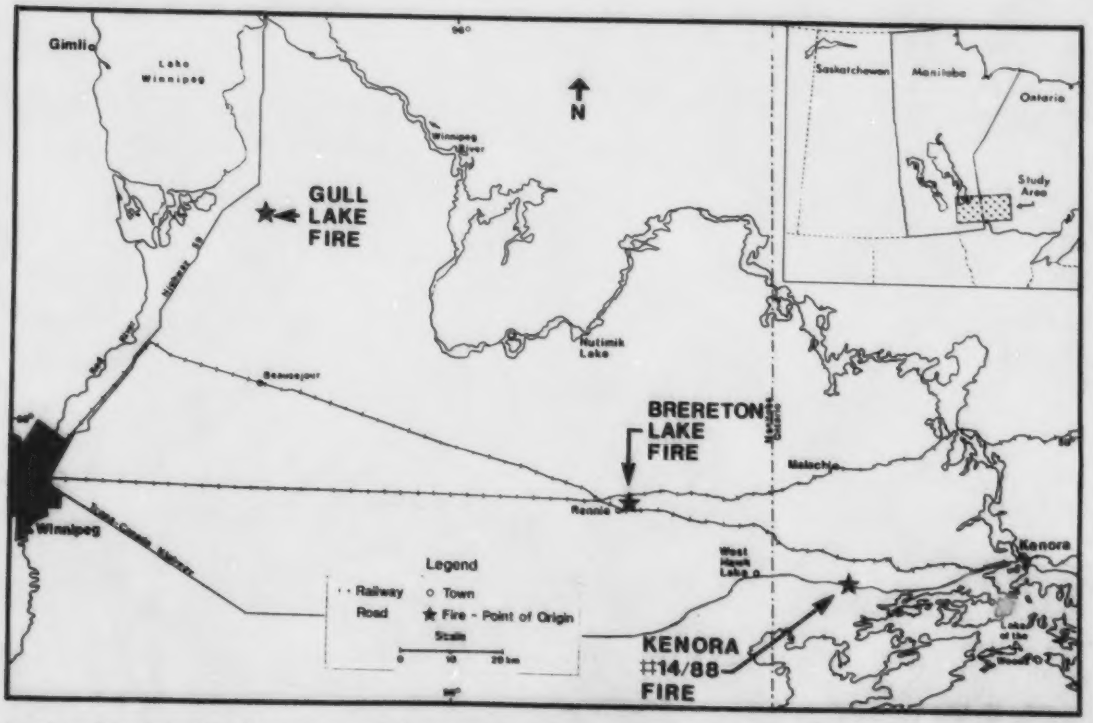

Gimli
Lake Winnipeg
96°
N
Winnipeg River
GULL LAKE FIRE
Highway 59
Red River
Nutimik Lake
Beausejour
BRERETON LAKE FIRE
Manitoba Ontario
Malachi
Rennie
Winnipeg
Trans-Canada Highway
Kenora
West Hawk Lake
Lake of the Woods
KENORA #14/88 FIRE
Legend
Railway
Road
Town
Fire - Point of Origin
Scale
0
10
20 km
Saskatchewan
Manitoba
Ontario
Study Area

FIG. 1. Location of the Gull Lake, Brereton Lake and Kenora #14/88 Fires in southeastern Manitoba and northwestern Ontario.

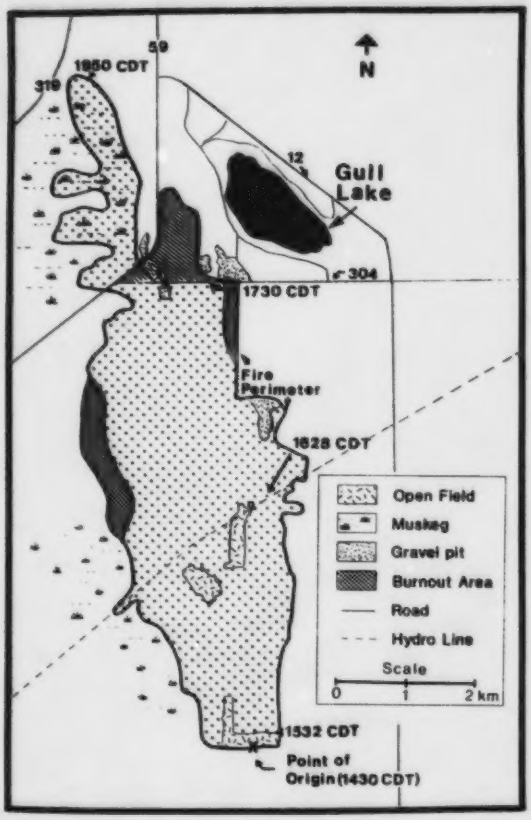

1850 CDT
59
319
N
12
Gull Lake
304
1730 CDT
Fire Perimeter
1628 CDT
Open Field
Muskeg
Gravel pit
Burnout Area
Road
Hydro Line
Scale
0
1
2 km
1532 CDT
Point of Origin (1430 CDT)

FIG. 2. Position of the head fire and final perimeter of the 1988 Gull Lake Fire in southeastern Manitoba.

BRERETON LAKE FIRE

The Brereton Lake Fire also started on May 1, 1988. A progress map of this man-caused fire is presented in Hirsch (1989). Its point of origin was near the town of Rennie along side the Canadian Pacific Railway (CPR) tracks approximately 120 km east of Winnipeg (Fig. 1). It was detected and reported at 1540 CDT at a size of less than 0.1 ha. The fire crowned almost immediately and began spreading northward towards the Brereton Lake cottage subdivision. By 1634 CDT the head fire had travelled 1.5 km and was approximately halfway to Brereton Lake. At 1753 CDT it crossed the Canadian National Railway (CNR) tracks near the cottage subdivision, 3.1 km from its point of origin.

By the evening of May 1 crews were able to secure a fireline completely around the fire using natural firebreaks and hand constructed fireguards. A major suppression effort on May 2, involving the use of three CL-215 airtankers, prevented any further flare-ups from occurring. The final area burned was estimated at 1300 ha. Five cottages and a number of smaller outbuildings were destroyed by the fire. It was also noted that the fire spread primarily on the jack pine ridges where it would frequently torch but did not spread continuously through the tree crowns. Fire spread in the black spruce (Picea mariana) stands was minimal due to the moist duff layer which was still frozen just below the ground's surface.

KENORA #14/88 FIRE

The Kenora #14/88 Fire was initially reported to the local OMNR office at 1330 CDT on April 30, 1988. This fire was also man-caused and it was located just north of the Trans-Canada Highway approximately 30 km west of the town of Kenora (Figs.1 and 3). The

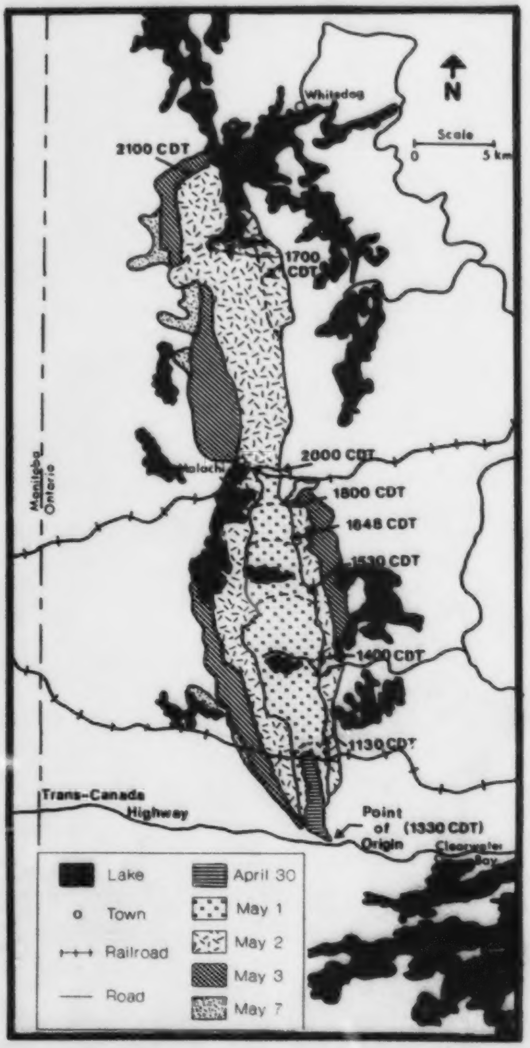

Whitedog
N
Scale
0
5 km
2100 CDT
1700 CDT
2000 CDT
Malachi
Manitoba
Ontario
1800 CDT
1648 CDT
1530 CDT
1400 CDT
1130 CDT
Trans-Canada Highway
Point of Origin (1330 CDT)
Clearwater Bay
Lake
Town
Railroad
Road
April 30
May 1
May 2
May 3
May 7

FIG. 3. Major fire runs and final perimeter of the Kenora #14/88 Fire in northwestern Ontario.

first suppression crew arrived at 1405 CDT and immediately asked for a second crew to be dispatched. By 1421 CDT the fire was estimated to be 2.0 ha in size and at 1545 CDT was reported to be "running". A birddog officer stated at 1548 CDT that a spot fire had developed 300 m west of the main fire and that the suppression efforts of the two crews and one CL-215 were not sufficient to hold the fire. At 1620 CDT the fire was estimated to be 140 ha in size and reached 500 ha by 1830 CDT when it was mapped by the fire behavior officer assigned to the overhead team.

At 0945 CDT on May 1 the fire had burned 798 ha and priority was given to protecting the cottage subdivisions in the area. By 1400 CDT the head fire had moved northward 6.0 km and crossed a secondary highway. It continued to spread northward and by 2000 CDT had travelled another 10.5 km at which time it crossed the CNR tracks by the hamlet of Malachi placing this subdivision in serious danger of being overrun by the fire.

On May 2, continued dry windy weather pushed the fire northward for another major run of almost 19 km. On-site observations made that afternoon indicated a consistent head fire rate of spread of 20 m/min with multiple torching and spot fires up to 500 m. Maximum flame heights during the major torching episodes reached 80 m.

The northerly spread of the fire diminshed on May 3 as the fire reached an area of high, well-exposed open bedrock with a sparse covering of jack pine. A fuel type change to predominantly overmature hardwoods along the northwestern flank also slowed the fire spread considerably. A change in weather resulted in no major fire growth on May 4-6 however, a few small outbreaks did occur on the northwest flank on May 7 after which no further expansion in the fire's perimeter occurred. When declared out, the fire was approximately 43.5 km in length and 9.0 in breadth at its widest point. The final size of the fire was estimated to be 22 700 ha.

Fuels

The area where these three fires occurred is located at the western edge of the Great Lakes-St. Lawerence forest region and the southern limit of the boreal forest (Rowe 1972). The Brereton Lake and Kenora #14/88 fire areas are characterized by sparsely stocked stands of jack pine situated on pre-cambrian "rock ridges". The soils and organic mantels on these upland sites are shallow and dry very quickly after snowmelt, negating within days any effect of overwinter precipitation (Stocks and Flannigan 1987). Surface vegetation consists of grasses and small shrubs. A fairly continuous layer of ground lichen is present but dead-down woody fuels are light in most areas. Interspersed amongst these jack pine stands are well-stocked stands of lowland black spruce underlaid by a thick layer of feathermoss with only a few shurbs and little downed woody fuel. The Gull Lake Fire area was dominated by moderately-well stocked stands of semi-mature jack pine with occasional pockets of trembling aspen (Populus tremulodies). Surface fuels consisted of a heavier grass layer (estimated to be 2-3 t/ha) along with shrubs such as willows, and wild rose. Roundwood fuels were also light in this area.

The FBP System presently has 14 major fuel types (Lawson et al. 1985, De Groot 1987, Hirsch 1988b) of which two are Mature Jack Pine (C-3) and Immature Jack Pine (C-4). The Gull Lake Fire area is classified as fuel type C-4 while the Brereton Lake and Kenora #14/88 Fire areas are considered fuel type C-3.

Topography

The elevations of the Gull Lake, Brereton Lake and Kenora #14/88 Fire areas are 245 m, 330 m, and 365 m above mean sea level (MSL), respectively. The terrain is gently rolling and there are no sustained slopes or significant changes in elevation.

Antecedent Climatic Conditions

The fall of 1987 was unusually warm and dry in southeastern Manitoba and northwestern Ontario (Fig. 4). From September to December 1987 precipitation levels were 68, 62 and 56 percent of normal (Anonymous 1982) at the Atmospheric Environment Service (AES) weather stations in Gimli, Winnipeg and Kenora, respectively (Anonymous 1977). This trend continued from January to April 1988 except for the month of March when a heavy snowfall did occur, especially in the Kenora area. Monthly mean daily temperatures for the same three stations averaged 8.8°C above normal from September to December 1987 and 3.1°C above normal from January to April 1988.

Given this area is susceptible to rapid drying in the spring, the effect of overwinter precipitation is often not as critical as the weather which occurs after snowmelt. In April 1988 temperatures were slightly above normal temperatures but, more significantly, it was a very dry month (Table 1). Low amounts of precipitation and relative humidity (RH) values below 40% occurred on numerous days. These conditions resulted in a rapid depletion of the snow pack and a steady reduction in the moisture content of the forest fuels.

Attendant Weather Conditions

From April 26 to May 1 an upper level ridge began to build over the fire areas causing a continuous rise in surface temperatures. By May 1 this ridge was centered north of Lake Superior (Fig. 5) with a surface low and cold front positioned just west of the fire areas (Fig. 6). Figure 7 shows the movement of the surface cold front and how it was blocked by the upper ridge in central Manitoba. It also illustrates that along with the sharp temperature gradient that existed across this cold front, there were strong southerly winds just ahead of it. The vertical wind profile from interna-

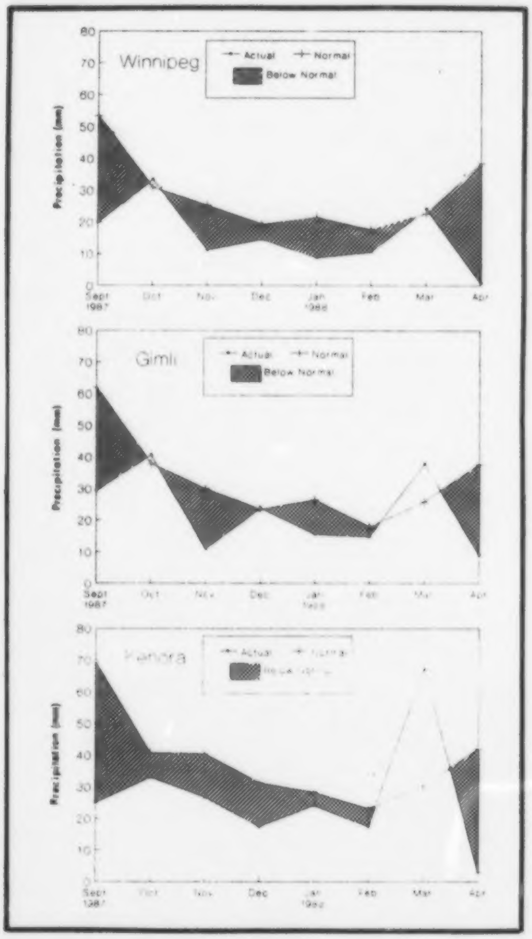


FIG. 4. Departure from the 1951-80 normal monthly precipitation amounts at three climatological stations in central Canada from September 1987 to April 1988.

Table 1. Climatological data for three meteorological stations in central Canada for April 1988 compared to the 1951-80 normals (where available).

Parameter	Winnipeg, MB		Gimli, MB		Kenora, ON	
	Actual	Normal	Actual	Normal	Actual	Normal
Precipitation (mm)	0.8	38.5	9.0	37.6	3.0	41.9
Daily temperatures (°C)						
Maximum	13.5	8.9	9.4	6.6	10.0	7.8
Minimum	-3.4	-2.2	-2.6	-4.0	-2.0	-2.5
Mean	5.1	3.4	3.4	1.3	4.0	2.7
No. of days RH ≤ 40%	23	n/a	10	n/a	22	n/a
Date of snow-free cover	04/02	04/11	04/08	04/20	04/09	04/26

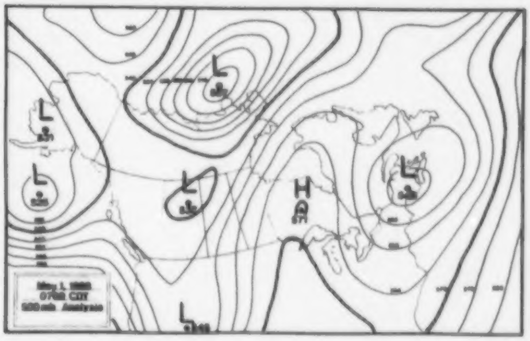


FIG. 5. 500 mb or 50 kPa chart for May 1, 1988, 0700 CDT.

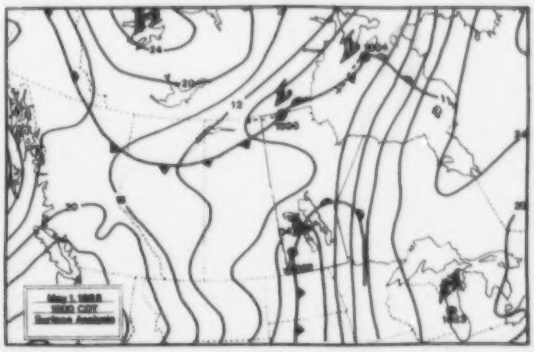


FIG. 6. Surface weather analysis for May 1, 1988, 1300 CDT.

tional Falls, Minnesota, on May 1, at 0900 CDT (Fig. 8), indicates that a low-level jet wind (Byram 1954, Alexander et al. 1983) was also present with the maximum velocity "point" located at 1220 m above the surface. Similar wind profiles also existed on April 30 and May 2. These strong surface and lower atmospheric winds were undoubtedly the major contributing factor to the rapid spread rates on all three fires.

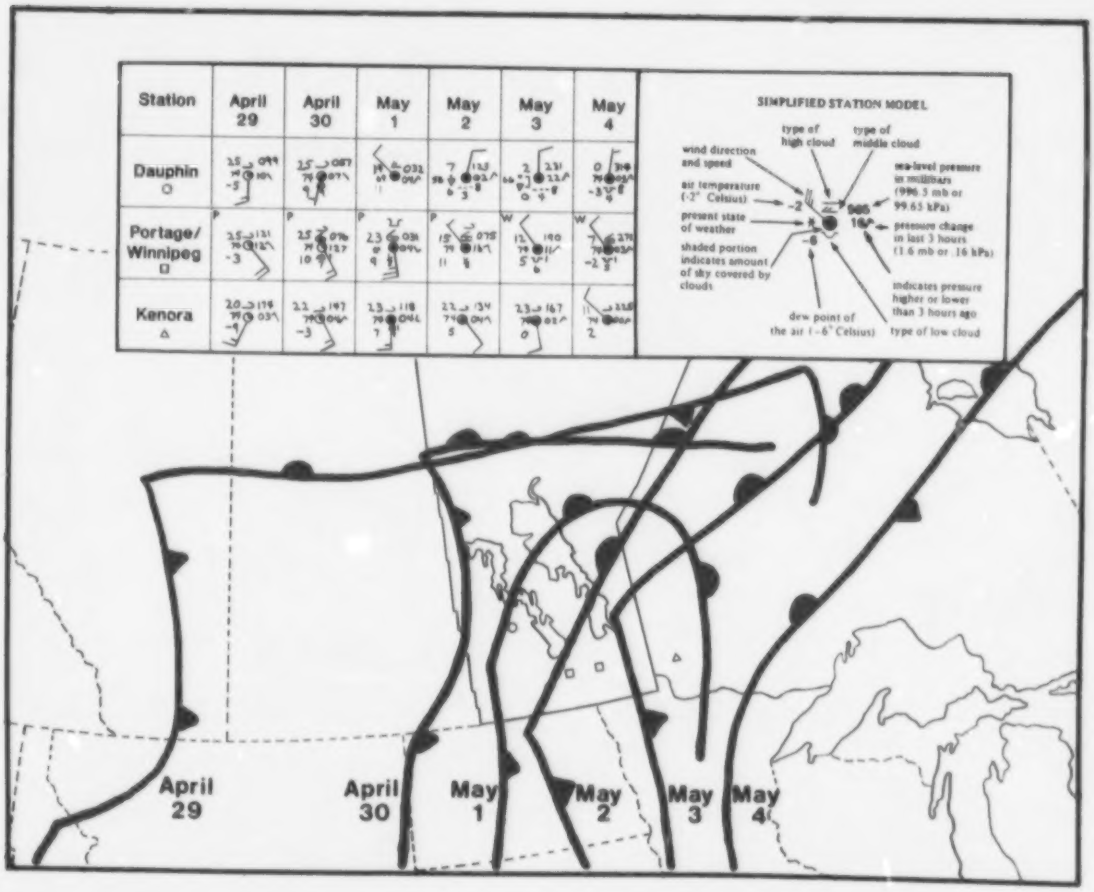

Station
April 29
April 30
May 1
May 2
May 3
May 4
Dauphin
Portage/ Winnipeg
Kenora
SIMPLIFIED STATION MODEL
type of high cloud
type of middle cloud
wind direction and speed
sea-level pressure in millibars (996.5 mb or 99.65 kPa)
air temperature (-2° Celsius)
present state of weather
pressure change in last 3 hours (1.6 mb or .16 kPa)
shaded portion indicates amount of sky covered by clouds
indicates pressure higher or lower than 3 hours ago
dew point of the air (-6° Celsius)
type of low cloud
April 29
April 30
May 1
May 2
May 3
May 4

FIG. 7. The 1300 CDT location of surface frontal systems in west-central Canada from April 29 to May 4, 1988. Surface weather information for three stations is also denoted.

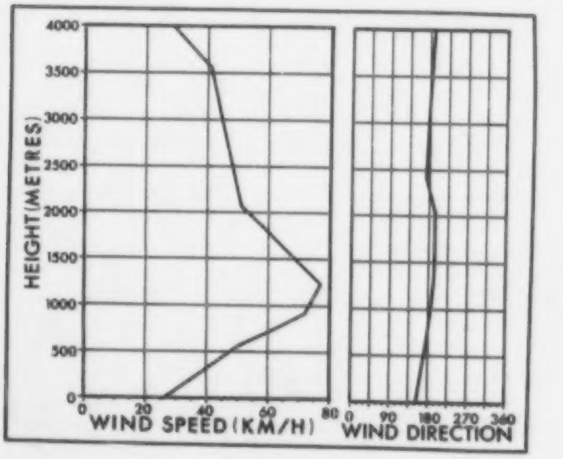


FIG. 8. Vertical wind profile above International Falls, MN, on May 1, 1988, 0900 CDT.

Ironically, while wildfires were burning out of control and destroying homes in eastern Manitoba the western section of the province was experiencing severe flooding. This was due to heavy rainfalls from the surface low which had settled directly over this area. This sharp and dramatic contrast in precipitation is exemplified by the fact that Swan River received 70.4 mm of precipitation from April 29 to May 3 while Portage la Prairie and Sprague (approximately 200 and 400 km eastward) received 9.4 mm and nil precipitation, respectively.

Fire Danger Indexes

The 1300 CDT fire weather observations and the calculated Canadian Forest Fire Weather Index (FWI) System values (Canadian Forestry Service 1984, Van Wagner and Pickett 1985, Van Wagner 1987) for each of the days with major runs are given in Table 2. A number of points are noteworthy. First, the Fine Fuel Moisture Code (FFMC) on the days the fires started

Table 2. Fire weather observations and fire danger indexes at 1300 CDT on the days of major fire runs at the Gull Lake, Brereton Lake and Kenora #14/88 Fires.

Calender date (1988)	(°C)	Dry-bulb temp. (%)	RH (km/h)	10-m open wind Speed Direction	FWI System components FFMC	DMC	DC	ISI	BUI	FWI
Gull Lake[a]										
May 1	20.4	43	24.0	SE	90.1	25	137	14.5	34	23
Brereton Lake[b]										
May 1	22.5	40	27.5	SE	91.0	40	260	20.9	58	39
Kenora #14/88[c]										
April 30	22.3	20	31.0	SE	94.8	32	61	40.4	32	45
May 1	23.2	35	31.0	SE	92.6	36	67	29.5	36	39
May 2	22.3	33	22.0	E	92.4	40	74	18.4	40	30

[a] Observations from the AES station at Gimli, MB (222 m MSL) located 40 km northwest of the Gull Lake Fire area (Fig. 1).

[b] Observations from the West Hawk Lake, MB (331 m MSL) and Nutimik Lake, MB (302 m MSL) fire weather stations were averaged to obtain these values. These stations are operated by MNR and are located 30 km southeast and north of the Brereton Lake Fire area, respectively (Fig. 1).

[c] Observations from the AES station at Kenora, ON (411 m MSL), located 30 km east of the Kenora #14/88 Fire area (Fig 1).

were all above 90 which implies a high ignition potential, especially for man-caused fires. Second, the high wind speeds resulted in extreme Initial Spread Index (ISI) values and, in turn, high Fire Weather Index (FWI) values. This indicates that the fire's rate of spread would be rapid and that it would be the major factor contributing to a very intense fire. Third, the Duff Moisture Code (DMC), Drought (DC) and the Buildup Index (BUI) values were relatively low meaning fuel consumption would probably be restricted to the fine fuels and that there would be little mop-up difficulty.

Fire Behavior Characteristics

FORWARD RATE OF SPREAD

The FBP System permits the calculation of head fire rate of spread (ROS) based on the ISI, fuel type and ground slope (McAlpine 1987). For each of the major fire runs, an ISI value was determined on the basis of the hourly weather observations at the nearest AES meteorological station and a diurnal FFMC value (Alexander 1982). These computed ISI values are presented in Table 3 along with a comparison of the calculated and observed head fire rates of spread. The results show that for the fire runs at the Brereton Lake Fire and on May 1 at the Kenora #14/88 Fire the ROS values are very similar with only an 11% and 14% difference. However, the actual spread rates for the Gull Lake Fire run and the May 2 run of the Kenora #14/88 Fire were underestimated considerably by the FBP System while the April 30 run of the Kenora #14/88 Fire was overestimated.

A variety of factors may cause discrepencies between the actual and calculated head fire ROS values. This includes variations in fuel type, spatial differences in weather conditions, or the influence of upper level winds on the fire, to mention only a few. To emphasize this point, a second set of FBP System calculations were made for the overestimated and underestimated fire runs using alternative wind speed observations (Table 4). It is interesting to note that in this second comparison the variation between the actual and predicted spread rates is substantially smaller. The implications of this are three-fold. First, in some instances it may not be appropriate to use the observations from the weather station closest to a particular wildfire because they are not representative of conditions at the fire area. Second, even though hourly information is available from AES meteorological stations the present network does not provide the coverage required to consistently make site specific fire behavior predictions. Third, the "noon" fire weather observations and fire danger indexes recorded at provincial fire weather stations can only serve as a general guide to potential fire behavior because timely observations during peak burning periods are often not available. Thus, the only way to ensure reliable fire behavior predictions is to accurately measure the input parameters, and especially wind speed, at or very near the fire site on a near-real time basis.

Table 3. A comparison of the actual versus predicted forward rate of spread (ROS) for the major fire runs of the Gull Lake, Brereton Lake and Kenora #14/88 Fires based on the ISI values determined from the wind speed observations taken at the nearest AES weather station.

Calender date (1988)	Local time (CDT)	FBPS fuel type	10-m wind[a] (km/h)	Hourly ISI	Predicted		Actual	
					ROS (m/min)	Distance (m)	ROS (m/min)	Distance (m)
Gull Lake Fire								
May 1	1532-1628	C-4	30[b]	16.8	27.4	1 532	57.7	3 000
	1628-1730	C-4	28[b]	17.8	29.2	1 808	54.8	3 400
						3 340		6 400
Brereton Lake Fire								
May 1	1540-1753	C-3	30[c]	22.4	25.8	3 431	23.3	3 100
Kenora #14/88 Fire								
April 30	1545-2000	C-3	25[d]	26.6	34.9	8 902	21.6	5 500
May 1	1130-1400	C-3	33[d]	26.1	33.8	5 073	38.3	5 750
	1400-1530	C-3	31[d]	27.2	36.2	3 259	38.8	3 500
	1530-1648	C-3	32[d]	28.6	39.3	3 062	41.6	3 250
	1648-1800	C-3	23[d]	19.8	20.1	1 449	34.7	2 500
	1800-2000	C-3	20[d]	15.6	12.0	1 443	13.3	1 600
						14 286		16 550
May 2	0900-1700	C-3	25[d]	15.1	11.1	5 328	30.2	14 500
	1700-2100	C-3	18[d]	12.3	6.7	1 600	17.7	4 250
						6 928		18 750

[a] Wind speed observations are averaged over a 2-minute period.

[b] Observations from the AES station at Gimli, MB (222 m MSL) located 40 km northwest of the Gull Lake Fire area (Fig. 1).

[c] Based on on-site estimates by suppression personnel and substantiated by observations at the AES stations at Kenora, ON (75 km east; 411 m MSL), Winnipeg, MB (120 km west; 239 m MSL), and Sprague, MB (90 km south; 329 m MSL).

[d] Observations from the AES station at Kenora, ON (411 m MSL), located 30 km east of the Kenora #14/88 Fire area (Fig 1).

Table 4. A comparison of the actual versus predicted forward rate of spread (ROS) for selected major fire runs of the Gull Lake and Kenora #14/88 Fires based on the ISI values determined from wind speed observations taken at AES weather stations near the fire areas.

Calender date (1988)	Local time (CDT)	FBPS fuel type	10-m wind[a] (km/h)	Hourly ISI	Predicted		Actual	
					ROS (m/min)	Distance (m)	ROS (m/min)	Distance (m)
Gull Lake Fire								
May 1	1532-1628	C-4	48[b]	41.7	64.9	3 635	53.6	3 000
	1628-1730	C-4	45[b]	42.0	65.2	4 045	54.8	3 400
						7 680		6 400
Kenora #14/88 Fire								
April 30	1545-2000	C-3	19[c]	19.6	19.9	5 067	21.6	5 500
May 2	0900-1700	C-3	32[d]	21.5	23.8	11 424	30.2	14 500
	1700-2100	C-3	22[d]	15.0	10.9	2 622	17.7	4 250
						14 046		18 750

[a] Wind speed observations are averaged over a 2-minute period.

[b] Observations from the AES station at Winnipeg, MB (239 m MSL) located 75 km southwest of the Gull Lake Fire area (Fig. 1).

[c] Observations from the AES station at Sprague, MB (329 m MSL) located 95 km southwest of the Kenora #14/88 Fire area.

[d] Based on observations from the AES station at Kenora, ON (30 km east; 411 m MSL) of the mean a value of the 2-minute average wind speed and the maximum gust during the same time period.

FRONTAL FIRE INTENSITY

On the basis of the BUI and hourly ISI components of the FWI System, the major runs can be placed into Fire Intensity Class 5 for the jack pine fuel type (Alexander and De Groot 1988). This intensity class has the following characteristics:

"Intermittent crown fire to active crown fire development (at > 10,000 kW/m). Very difficult to control. Suppression must be restricted to the fire's flanks. Indirect attack with aerial ignition (i.e., helitorch and/or A.I.D. dispenser) may be effective. Violent physical behavior probable at frontal fire intensities > 30,000 kW/m (i.e., blow-up or conflagration type fire run); suppression action should not be attempted until burning conditions ameliorate".

Certainly this description was very indicative of the general fire behavior and the relative effectiveness of the various types of suppression activities during all of the major fire runs.

Concluding Remarks

The prediction of forest fire behavior has often been referred to as both a science and an art. Case studies such as this one only seem to reinforce this point. Unique weather phenomena and variations in fuels and topography will never allow any fire behavior predictions to be 100% correct. However, the potential for error can be reduced significantly if predictions are based on accurate and timely, on-site fire weather observations. Furthermore, as more quantitative information is collected on large, well-documented wildfires such as the Gull Lake, Brereton Lake and Kenora #14/88 Fires, the more exacting the FBP System will become in forecasting extreme fire behavior. Ultimately, this greater understanding of fire behavior will contribute to the development of fire management programs which are, in turn, efficient and cost-effective.

Acknowledgements

The author wishes to thank the many people who provided information concerning the behavior of each fire especially T. Gauthier and B. Enns of MNR and D. Larmand of OMNR. Special thanks are also extended to J. Bendell of AES for retrieving and compiling the meteorological data used in this paper and M. Alexander of Forestry Canada for his valuable review comments.

Endnotes

[1] Alexander, M.E., B.D. Lawson, B.J. Stocks, and C.E. Van Wagner. 1984. User guide to the Canadian Forest Fire Behavior Prediction System: rate of spread relationships. Interim ed. Environment Canada, Canadian Forestry Service Fire Danger Group, Ottawa, ON. [First printing July 1984; revision and second printing - Sept. 1984].

[2] Alexander, M.E., 1982a. Bibliography of wildfire case histories and studies. Canadian Forestry Service, Northern Forestry Centre, Edmonton, AB. Study NOR-05-191 File Report No. 4, 9 pp. [last revised April 1987].

References

ALEXANDER, M.E. 1982. Diurnal adjustment table for the Fine Fuel Moisture Code. Can. For. Serv., North. For. Res. Cent. For. Manage. Note No. 17.

ALEXANDER, M.E., AND W.J. DE GROOT. 1988. Fire behavior in jack pine stands as related to the Canadian Forest Fire Weather Index (FWI) System. Canadian Forestry Service, Northern Forestry Centre, Edmonton, AB. Poster (with text).

ALEXANDER, M.E., AND R.A. LANOVILLE. 1987. Wildfires as a source of fire behavior data: a case study from the Northwest Territories, Canada. In Postprint volume, ninth conference on fire and forest meteorology. American Meteorological Society, Boston, MA. pp. 86-93.

ALEXANDER, M.E., B. JANZ, AND D. QUINTILLIO. 1983. Analysis of extreme wildfire behavior in east-central Alberta: a case study. In Preprint volume, seventh conference on fire and forest meteorology. American Meteorological Society, Boston, MA. pp. 38-46.

ANONYMOUS 1977. METSTAT: Meteorological stations in Canada. Environment Canada, Atmospheric Environment Service, Central Service Directorate, Toronto, ON.

ANONYMOUS 1982. Canadian climate normals: 1951-80. Temperature and precipitation--prairie provinces. Environment Canada, Atmospheric Environment Service, Downsview, ON. Misc. Publ., 429 pp.

BYRAM, G.M. 1954. Atmospheric conditions related to blowup fires. U.S. Dept. Agric. For. Serv., Southeast. For. Exp. Stn. Stn. Pap. No. 35.

CANADIAN FORESTRY SERVICE 1984. Tables for the Canadian Forest Fire Weather Index System. 4th ed. Can. For. Serv. For. Tech. Rep. 25.

DE GROOT, W.J. 1987. Examples of Canadian Forest Fire Behavior Prediction System fuel types in Saskatchewan. Canadian Forestry Service, Saskatchewan District Office, Prince Albert, SK. Poster (with text).

HIRSCH, K.G. 1988a. An overview of the 1987 Wallace Lake Fire, Manitoba. Fire Manage. Notes 49(2):26-27.

HIRSCH, K.G. 1988b. Examples of Canadian Forest Fire Behavior Prediction System fuel types in Manitoba. Canadian Forestry Service, Manitoba District Office, Winnipeg, MB. Poster (with text).

HIRSCH, K.G. 1989. Documenting wildfire behavior: an example from the 1988 Brereton Lake Fire, Manitoba. Fire Manage. Notes 50 (1):45-48.

LAWSON, B.D., B.J. STOCKS, M.E. ALEXANDER, M.E. AND C.E. VAN WAGNER. 1985. A system for predicting fire behavior in Canadian forests. In Proceedings of the eighth conference on fire and forest meteorology. Edited by L.R. Donoghue and R.E. Martin. Society of American Foresters, Bethesda, MD. SAF Publ. 85-04. pp. 6-16.

MCALPINE, R.S. 1987. Two BASIC programs for fire danger and fire behavior computations. Can. For. Serv., North. For. Cent. For. Manage. Note No. 43.

ROWE, J.S. 1972. Forest regions of Canada. Can. For. Serv. Publ. No. 1300.

STOCKS, B.J. 1975. The 1974 wildfire situation in northwestern Ontario. Can. For. Serv. Inf. Rep. 0-X-232.

STOCKS, B.J., AND M.D. FLANNIGAN. 1987. Analysis of the behaviour and associated weather for a 1986 northwestern Ontario wildfire: Red Lake #7. In Postprint volume, ninth conference on fire and forest meteorology. American Meteorological Society, Boston, MA. pp. 94-100.

STOCKS, B.J., AND J.D. WALKER. 1973. Climatic conditons before and during four significant forest fire situations in Ontario. Can. For. Serv. Inf. Rep. 0-X-187.

STREET, R.B., AND B.J. STOCKS, 1983. Synoptic-scale fire weather in northwestern Ontario. In Preprint volume, seventh conference on fire and forest meteorology. American Meteorological Society, Boston, MA. pp. 9-12.

VAN WAGNER, C.E. 1987. Development and structure of the Canadian Forest Fire Weather Index System. Can. For. Serv. For. Tech. Rep. 35.

VAN WAGNER, C.E., AND T.L. PICKETT. 1985. Equations and FORTRAN program for the Canadian Forest Fire Weather Index System. Can. For. Serv. For. Tech Rep. 33.

Specification of Monthly Mean Anomalies of Fire Weather Elements from Concurrent Anomalies of the Mean 700 MB Height Field

W. H. KLEIN AND B. T. WHISTLER
Department of Meteorology
University of Maryland
College Park, Maryland

Abstract

Monthly mean anomalies of fire weather elements observed about 1 PM local standard time at 116 surface stations in the contiguous United States from 1964 to 1983 were correlated with concurrent 700 mb height anomalies at 121 grid points in North America and surrounding oceans. The data were processed by a forward stepwise selection program with statistical significance determined by a Monte Carlo technique. This procedure yielded multiple regression equations for specifying the temperature, dewpoint and wind speed for each month and city from the field of simultaneous 700 mb height plus the previous month's local value of that weather element. In addition, specification equations were derived for the number of rainy days per month in each of 60 climate divisions across the nation.

This paper discusses the characteristics of the specification equations, with emphasis on month-to-month changes and regional differences. On the average, the equations explain approximately 68% of the temperature variance, 59% of the dew point variance, 41% of the precipitation variance and 37% of the wind variance by means of 2-3 variables. They can be be readily applied to prognostic monthly mean 700 mb height anomalies routinely produced by the Climate Analysis Center of the National Weather Service to yield monthly outlooks for each fire weather element in map form.

Résumé

Les anomalies moyennes mensuelles d'éléments météorologiques favorables aux incendies observées vers 13 h, heure normale locale, dans 116 stations en surface de la partie continentale des États-Unis de 1964 à 1983 ont été corrélées avec des anomalies concomitantes du champ de hauteur à 700 mb de 121 points de grille situés en Amérique du Nord et dans les océans environnants. Les données ont été traitées par un programme de sélection progressif, l'importance statistique ayant été déterminée par une technique de Monte^Carlo. Cette démarche a donné des équations de régression multiple pour caractériser la température, le point de rosée et la vitesse du vent de chaque mois et ville du champ de hauteur simultanée à 700 mb, en plus de la valeur locale de cet élément météorologique au cours du mois précédent. De plus, des équations de caractérisation ont été obtenues pour le nombre de jours de pluie par mois dans chacune des 60 divisions climatiques du pays.

Ce papier discute des caractéristiques des équations de caractérisation, avec l'emphase sur les changements de mois en mois et les différences régionales. En moyenne, les équations servent à expliquer 68% de la variance de la température, 59% de la variance du point de rosée, 41% de la variance de la précipitation et 37% de la variance du vent en utilisant 2-3 variables. Elles peuvent être facilement appliquées aux anomalies dans la prognostique moyenne mensuelle du champ de hauteur à 700 mb routinement produite par le Climate Analysis Center du National Weather Service afin de fournir des perspectives mensuelles de chaque élément forêt-météo sous forme de cartes.

Introduction

Specification of monthly mean surface weather elements from concurrent fields of 700 mb height anomaly (HA) can help the U.S. Forest Service evaluate the potential for wildland fires in the United States. We have therefore derived multiple regression equations for anomalies of monthly precipitation frequency (PF), midday temperature (T), dewpoint (D or Td), relative humidity (RH) and wind speed (V) by forward selection (screening) of potential HA predictors. Although computed from a long period of observed data, these equations will be applied to monthly mean values of HA forecast routinely in the Climate Analysis Center (CAC). Because of errors in these prognostic values, the specification equations will lose considerable skill in forecast operations.

Method and Results

We first derived specification equations for PF (the number of days with precipitation ≥ 0.10 inches) at each of 60 climate divisions across the United States from 30 years of data (1951-1980) by pooling each month with its two immediately adjacent months and screening the simultaneous HA at a network of 79 grid points in North America and vicinity. Figure 1 shows the annual cycle of the average reduction of variance (RV) (multiple correlation squared) for PF (dashed)

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

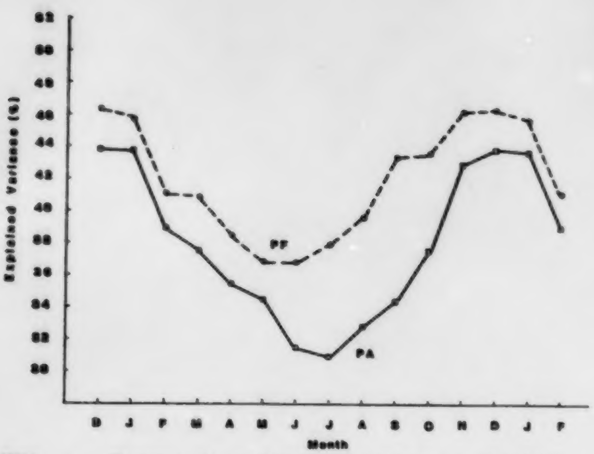


FIG. 1. Percent of variance explained by monthly precipitation specification equations, averaged over 60 climate divisions, as a function of concurrent 700 mb mean height anomalies at 79 grid points for frequency (PF) and amounts (PA) during 1951-1980.

and PA (precipitation amounts at the same 60 divisions for the same period of record). Note that PF outperforms PA each month, with greatest difference in the summer when precipitation is difficult to specify because of localized convective activity.

We next obtained a set of 3-hourly surface observations at 116 stations plotted in Figure 2 for the 20-year period: 1964-1983. After computing monthly mean values of T, D, RH and V observed at approximately 1300 h, local standard time, we selected a representative subset of 58 stations for experimentation with 3-month seasons centered on Feb., May, Aug. and Nov. For each of the above weather elements, we screened HA at a field of 121 grid points (Fig. 3). The results (Fig. 4) show that the RV, averaged over all months and stations, had the following rank: T (best), D, PF, RH and V (worst). We were able to increase the RV by about 4%, on the average, by including the previous month's value of the predict and (dependent variable) as an additional potential predictor (local persistence). However, previous values of other local elements (such as D to predict T) or of the same element at the entire network of 58 stations (such as one station's D to predict another's D) did not produce meaningful improvement. Also, we could not increase the RV of V by screening the field of 700 mb geostrophic wind speeds and components instead of heights. In view of the above results, we decided to omit RH from further consideration and to derive final specification equations for T, D and V from HA and local persistence only.

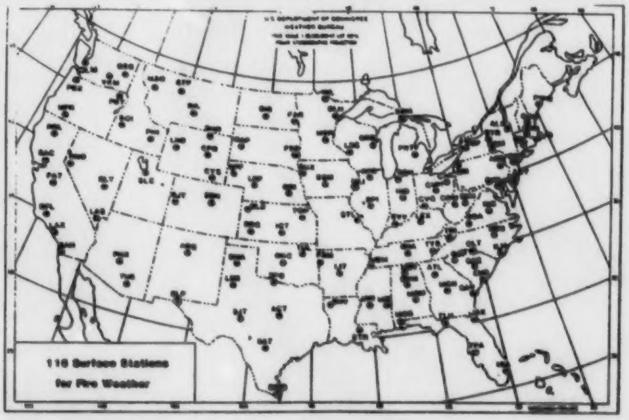


FIG. 2. Locations and call letters of 116 surface stations used in this study.

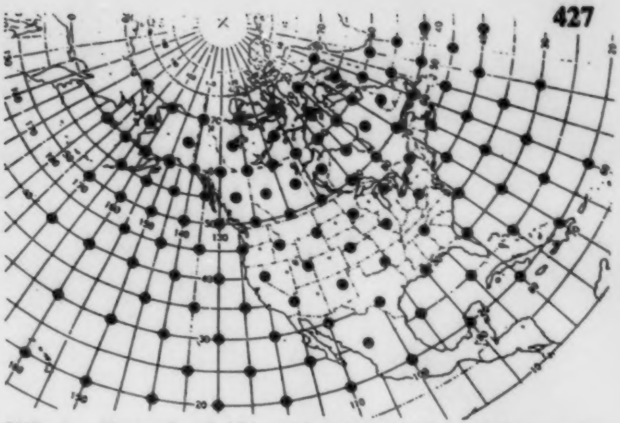


FIG. 3. Network of 121 grid points used to delineate the field of 700 mb height.

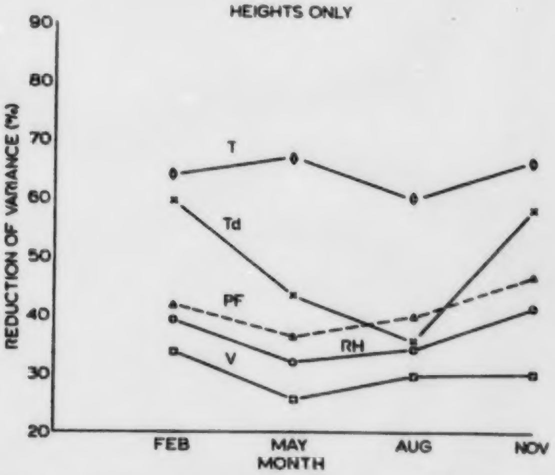


FIG. 4. Average reductions of variance for 58 stations during Feb., May, Aug. and Nov. obtained by specifying temperature, dewpoint, relative humidity and wind speed (solid) over a 20-year period from the height field of Fig. 3. Comparable statistics for precipitation frequency at 60 climate divisions over 30 years are dashed.

Figure 5 shows the annual cycle of persistence in terms of the one-month lag autocorrelation coefficient, averaged over all 116 stations of Fig. 2, separately for

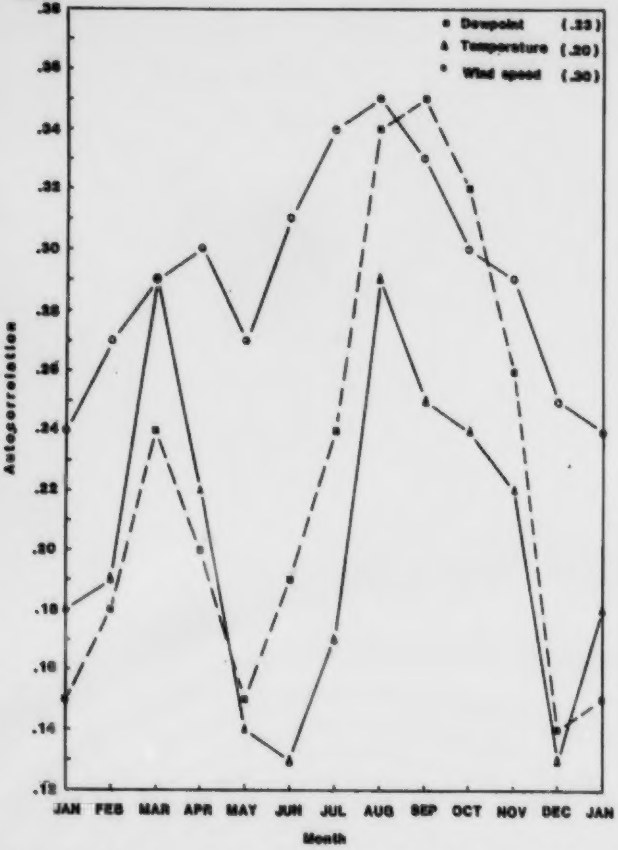


FIG. 5. Month-to-month variations of the one-month lag autocorrelation for surface dewpoint, temperature and wind speed, averaged over 116 stations of Fig. 2. Annual average values of each element are given in the upper right hand corner.

D, T and V. All three elements exhibit maxima in month-to-month persistence in late summer and late winter and minima in late spring and late fall. Annual average values (upper right hand corner) are slightly higher for D (.23) than for T (.20), perhaps because of persistence of soil moisture. However, the unexpectedly high average autocorrelation for V (.30) cannot be readily explained.

In the results described thus far, we used a cut-off criterion of approximately 99% on the classical F-test as an estimate of the true 95% significance level for terminating selection of variables in the specification equations. To establish a more exact criterion, we performed a series of Monte Carlo simulations summarized in Figure 6. It shows that the 95th percentile of F-values obtained by screening 1200 randomly shuffled samples of our data (critical F) increases as the number of potential predictors increases from 1 (classical) to 79 (for PF) to 121 (for T, D and V). Since the critical F also varies slightly with month and element, we made separate Monte Carlo runs for each of these factors and used the results as our primary tool in selecting the final specification equations.

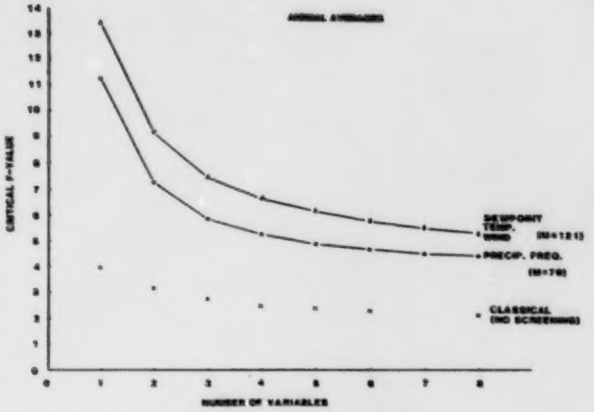


FIG. 6. Mean annual values of the critical F statistic as a function of number of terms in multiple regression equation and number of potential predictors (M). The critical values represent the 95th percentile of all F's obtained by screening randomly shuffled data for 121 predictors (mean of curves for D, T and V) and for 79 predictors (PF). Crosses denote classical F values without screening.

The statistics involved in selecting a sample equation are illustrated in Table 1 for D during summer months at Scottsbluff, NE (BFF). The first predictor selected is the HA at 50°N, 100°W., just northeast of BFF, with an RV of 20% and F of 14.6. The second variable is the previous month's dewpoint, which adds 15% to the total RV. The third predictor is the HA at 30°N, 120°W, well southwest of BFF, which adds 11% to the RV. The negative sign of its regression coefficient, in conjunction with the positive sign for the first variable, indicates that high (low) dewpoints are favored by anomalous flow of moist (dry) air from the southeast (northwest). The selection process was stopped at this point, with a standard error of 2.5°F and 46% of the variance explained by only three terms, because no other predictor made good synoptic sense or produced an F in excess of the critical value.

Specification equations similar to those in Table 1 have been selected for each station, month and weather element. The annual cycle of RV for D and T is plotted in Figure 7, where each point represents the mean over all 116 stations of Figure 2. Although T exhibits higher values than D each month, the difference in RV is very small in January, when both elements are well specified by the large-scale 700 mb circulation. However, the difference is very large in July, when D is apparently very sensitive to boundary layer phenomena and small-scale factors (e.g., evaporation of soil moisture) which are not well represented by the large scale 700 mb pattern.

Table 1. Summary of the stepwise regression statistics obtained by screening monthly mean surface dewpoint at Scottsbluff, NE (42°N, 103°W) during June, July and August, 1964-1983, as a function of the concurrent field of 700 mb height anomalies. The critical F-values were determined by a Monte Carlo procedure. The final equation selected for use in specification is starred.

Step	Grid point for height	Reg. coeff. on entry	Added RV(%)	Total RV(%)	Computed F-value	Prob. level(%)	Critical F-value	SE (°F)
1	50°N,100°W	+0.073	20.1	20.1	14.6	99.9	13.7	3.0
2	PREV.DEWP.	+0.396	15.1	35.2	13.3	99.9	10.0	2.7
3*	30°N, 120°W	-0.105	10.8	46.0	11.2	99.8	8.8	2.5
4	60°N,70°W	+0.023	4.0	50.0	4.4	95.8	7.2	2.4
5	60°N,100°W	-0.045	3.8	53.8	4.5	96.1	6.6	2.3

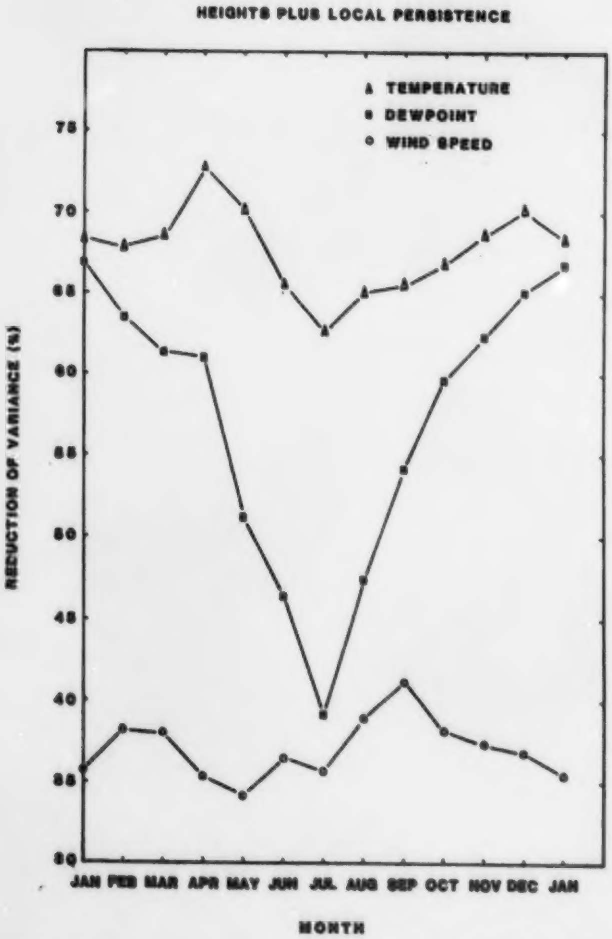


FIG. 7. Month-to-month variations in the reduction of variance of specification equations for surface dewpoint and temperature, averaged over 116 stations of Fig. 2.

Conclusion

On an overall basis, for all stations and all months, our final specification equations explain approximately 67.7% of the temperature variance by means of 3.5 variables. The corresponding statistics for dewpoint are 56.5% and 3.1 terms, for precipitation frequency 41.4% and 2.8 terms, and for wind speed 37.2% and 2.4 terms. Since large geographical and temporal variations are evident in these and other climatological statistics, we are analyzing, for each element and each month, maps of the explained variance, auto- correlation, mean and standard deviation. These maps should help forecasters interpret the final specification equations and the Forest Service prepare monthly fire-weather outlooks.

Acknowledgments

This research was supported by the U.S. Department of Agriculture, Forest Service, under Cooperative Agreement No PSW-87-0023CA. Surface data was obtained from the Forest Service in East Lansing, MI; climate division data from Creighton University, NE; and 700 mb heights from CAC in Camp Springs, MD. We thank F. Fujioka, M. McCutchan and B. Main of the Forest Service; A. Douglas and P. Englehart of Creighton University; D. Gilman of CAC and F. Baer, H. Bloom and R. Yang of the University of Maryland for help in various aspects of this project.

The Relationship Between Mean Monthly Fire Potential Indices and Monthly Fire Severity

M. H. MCCUTCHAN
Pacific Southwest Forest and Range Experiment Station,
Forest Service, U.S. Department of Agriculture,
Riverside, California

W. A. MAIN
North Central Forest Experiment Station,
Forest Service, U.S. Department of Agriculture,
East Lansing, Michigan

Abstract

Thirty-day forecasts of fire potential are needed, and can be computed using a variety of monthly fire weather indices. But which indices are most related to monthly fire severity? Correlation analysis was used to determine the relationships between mean monthly fire potential indices and monthly measures of fire severity at 16 National Weather Service (NWS) stations/National Forests combinations across the contiguous United States for the period 1970 to 1983. The fire potential indices used included standard weather variables, measures of drought, weather-driven fire indices, and precipitation frequency. Six measures of fire severity were used: fires, Class C+ fires (fires 10 acres or greater), acres burned, costs, fire days, and Class C+ fire days. The correlation analysis identified the mean monthly fire potential indices that best track measures of fire severity. Thirty-day fire potential forecasts can be made using the identified fire potential indices.

Résumé

Des prévisions 30 jours des dangers de feu sont nécessaires, et peuvent être calculées à l'aide d'une variété d'indices mensuels forêt-météo. Mais quels indices sont les plus reliés à la gravité mensuelle des incendies? Une analyse de corrélation a été utilisée pour déterminer les relations entre les indices de danger mensuels moyens de feu et les mesures mensuelles de la gravité des incendies dans 16 stations combinées du National Weather Service/forêts nationales d'un bout à l'autre de la partie continentale des États-Unis pour la période allant de 1970 à 1983. Les indices de danger de feu utilisés comprenaient des variables météorologiques normalisées, des mesures de la sécheresse, des indices d'incendie associés à la météo et la fréquence de la précipitation. Six mesures de la gravité des incendies ont été utilisées: incendies, incendies classe C+ (incendies de 10 aires ou plus), nombre d'acres détruits par le feu, coûts, jours d'incendies, et jours d'incendies classe C+. L'analyse de corrélation nous aidera à identifier les indices mensuels moyens de danger de feu qui suivent le mieux les mesures de la gravité des incendies. Cela nous permettra d'effectuer des prévisions des dangers de feu pour 30 jours à l'aide des indices de danger de feu identifiés.

Introduction

Planning for the efficient use of national fire suppression resources requires substantially greater lead time than comparable planning on a local scale. At the Boise Interagency Fire Center, a 30-day forecast of United States fire severity is prepared to depict fire potential nationwide, support requests for supplemental fire-fighting funds, and aid national fire-prevention efforts (Burgan and Hartford 1988). The National Fire-Danger Rating System energy release component and burning index are forecast in each of 46 polygons that cover the contiguous United States (Deeming et al. 1977). Research is currently in progress to develop monthly mean anomaly forecasts of afternoon dry-bulb and dewpoint temperatures, windspeed, and precipitation amount and frequency (Klein and Whistler 1989). With this information, corresponding 30-day forecasts of fire potential can be computed, using any of a variety of fire weather indices, which are functions of the weather variables listed above. But first we must determine the monthly fire weather indices that are most related to or best correlated with monthly fire severity measures. This paper describes the selection of fire weather indices, which are--in some sense--optimal predictors of monthly fire severity. The second section describes the method used to screen the indices. Results of analysis from selected National Forests are given in the third section. In conclusion, candidate fire weather indices are identified for different sections of the nation, based on the results of these data.

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

Methods

We obtained weather and fire data from 16 National Weather Service (NWS) stations and nearby National Forest locations in the United States (Fig. 1). We tried to pick a wide cross section of locations, ensuring that representative vegetation classes and climatic regions were considered.

Thirteen weather variables/indices and 6 measures of fire severity were correlated at each of the 16 locations. We arbitrarily selected the significance level at 0.05. Therefore only cases with correlation coefficients greater than 0.53 were significant.

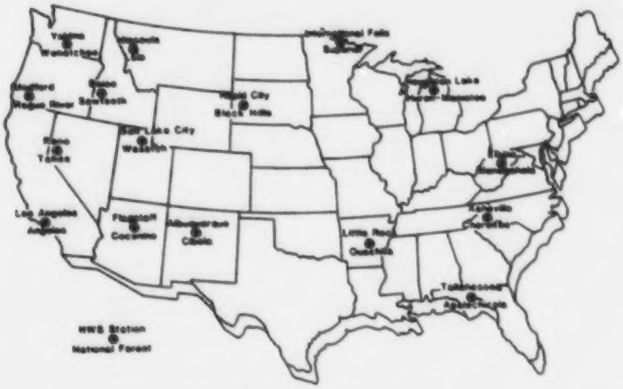


FIG. 1. Locations of 16 National Weather Service stations and nearby National Forests.

FIRE DATA

Individual fire reports (form 5100-29) for the 16 National Forests were obtained from the Boise Interagency Fire Center, for the period 1970 to 1983. Monthly fire severity was summarized for the following measures:

1. Fires
2. Class C+ Fires (Fires 10 acres or greater)
3. Acres burned
4. Suppression costs (Individual cost classes were summed and the result multiplied by the consumer price index for each year. This resulted in a constant dollar cost over the study period.)
5. Fire days (days with at least one fire)
6. Class C+ Fire days (days with at least one Class C+ Fire)

The order of the fire activity measures has no particular meaning. Fires (1) are easily understood by everyone and are the measure we focus on in this paper. Acres and costs tend to have the largest variability and lowest correlation coefficents with weather as shown by Flannigan and Harrington (1987). Class C and larger fires are of particular interest to fire managers, but occur infrequently in our sample.

Monthly summary data for all measures of fire severity were obtained for every month at each location. We then used fire occurrence to determine the fire season at each location to compare with the weather variables (Haines and Johnson 1975). Months with less than 10 percent of the number of fires occurring during the peak month were eliminated from the study. Out of a possible 192 station months for study, 104 were judged to be in the fire season, and used in this study.

WEATHER DATA

We obtained daily weather data from 16 NWS first order reporting stations in the United States. These stations are primarily located at airports near major cities. We chose NWS stations instead of fire weather stations for two reasons. First, the monthly mean anomaly forecasts are being formulated for these stations; and second, the NWS stations have little or no missing data. We considered using fire weather stations because of their proximity to the fires, but most of these stations have incomplete data sets.

WEATHER VARIABLES

Using daily weather observations, we were able to obtain monthly mean or total values of the following variables:

1. Precipitation amount, cm. (PA)
2. Precipitation frequency (days > 0.25 cm.) (PF)
3. 1300 LST temperature, °F (T)
4. 1300 LST relative humidity, % (RH)
5. 1300 LST windspeed, mph (W)

These five weather variables were tested as significant predictors of fires. Except for precipitation frequency, these weather variables are similar to those that fire weather observers would record on a daily basis (Fisher and Hardy 1976).

CALCULATED INDICES

With the above weather variables available, more complicated expressions of fire-danger are possible. The only monthly fire-danger indices found in the literature were formulated by Chandler et al. (1983). Their three indices used monthly mean values of temperature and relative humidity as input, and provided outputs in meaningful units of fire-danger.

1. Intensity component (INT):

$$INT = (110 - 1.373(RH)) - 0.54(10.2 - T) \qquad (1)$$

where RH = monthly mean 1300 LST relative humidity, (%)
and T = monthly mean 1300 LST temperature (°C).

The intensity component equation was incorrect in their text. Personal communications with the authors indicate that Eq. (1) is the correct formulation.

2. Spread component (SPD):

$$SPD = 124 \times 10^{-0.0142(RH)} \quad (2)$$

3. **Burning index (BI):**

$$BI = (INT)(SPD)/60 \quad (3)$$

where INT = intensity component and SPD = spread component.

Two other calculated indices are the equilibrium moisture content and the fire weather index.

1. The equilibrium moisture content (EQMC) equation was developed by Nelson (1964) for the 1964 National Fire-Danger Rating System. For the range of monthly mean temperatures and relative humidities, Eq. (4) is equivalent to that in Simard (1968).

$$EQMC = e^{(0.8872 + 0.8507\ln(RH) - 0.4747\ln(T))} \quad (4)$$

where T = mean monthly 1300 LST temperature in °F, and RH = mean monthly 1300 LST relative humidity.

2. The fire weather index (FWI) was developed by Fosberg (1978).

$$FWI = n\,(1 + W^2)^{1/2}/0.3002 \quad (5)$$

where W is the windspeed (mph) and n is a moisture damping coefficient

$$n = 1 - 2\,(m/30) + 1.5\,(m/30)^2 - 0.5\,(m/30)^3 \quad (6)$$

where m is the equilibrium moisture content.

DROUGHT INDICES

The NWS issues monthly drought indices. These indices have been shown to correlate with fire occurrence (Haines and Main, 1978a, Haines et al. 1978b). However, 30-day forecasts of these indices are not available at this time. In particular, the Z-Index, or moisture anomaly index, a required step in calculating the Palmer Drought Index (Palmer 1965), has a high correlation with fire occurrence. We obtained historical monthly values of the following three drought indices for the period 1931 to 1982 from NOAA National Climatic Data Center (NCDC):

1. Palmer Drought Index (PDI)
An agricultural drought index that compares current soil moisture conditions to the long term normal or expected conditions.

2. Palmer Hydrological Index (PHI)
A water-balance index that compares current to expected conditions. The PHI will often be the same as the PDI.

3. Z-index (Z)
The current monthly departure from normal (average) moisture balance. This index has NO memory and can be "WET" during long drought periods.

Results

We used simple correlation methods to search for significant fire severity predictors using the discussed weather variables and calculated indices. Each of the 104 monthly data sets used in the study contained 14 years of data. Individual correlations had to exceed 0.53 to be significant at the 5 percent level. Correlations for July between the NWS station at Rapid City, South Dakota and the Black Hills National Forest show how well fire severity might be predicted at a single forest for a single month (Table 1). The highest correlation with fire occurrence was PHI (r = -0.86), and with costs it was FWI (r = 0.68). These correlations are between observed monthly weather variables and indices and monthly fire severity measures. When we say "predicted" we would be using 30-day forecast weather variables and indices. Consequently, it would require perfect forecasts for the correlations to hold exactly.

We also looked at which weather variable or calculated index has the highest correlation with the measures of fire severity at 14 NWS station/National Forest combinations (Table 2). The Cherokee and Monongahela National Forests are not listed because they did not meet the criteria for a fire season in July. As occurred at Rapid City, South Dakota/Black Hills National Forest, there were strong relationships between the mean monthly weather variable and calculated indices and monthly fire severity at International Falls, Minnesota/Superior National Forest, and Missoula, Montana/Lolo National Forest. The relationships were weak at Yakima, Washington/Wenatchee National Forest, and Boise, Idaho/Sawtooth National Forest.

Table 1. Correlation coefficients between the 13 monthly mean weather variables and calculated indices at the Rapid City, South Dakota, National Weather Station and six measures of monthly fire severity at the Black Hills National Forest for July 1970 to 1983. Highest correlation for each measure of monthly fire severity is underlined.

Variables and Indices	Fire severity measure					
	Fires	Class C+ Fires	Acres	Costs	Fire Days	Class C+ Fire Days
PDI	-0.84	$\underline{-0.66}$	-0.51	-0.48	$\underline{-0.91}$	-0.53
PHI	$\underline{-0.86}$	-0.65	-0.53	-0.49	-0.90	$\underline{-0.54}$
Z	-0.61	-0.51	-0.50	-0.48	-0.67	-0.35
PA	-0.26	0.11	-0.35	-0.40	-0.18	0.30
PF	-0.52	-0.10	-0.54	-0.61	-0.51	0.03
T	0.79	0.49	0.57	0.59	0.83	0.40
RH	-0.56	-0.35	-0.53	-0.56	-0.58	-0.17
W	0.36	0.26	0.53	0.53	0.34	0.20
INT	0.60	0.37	0.55	0.58	0.61	0.19
SPD	0.62	0.38	0.60	0.62	0.62	0.18
BI	0.65	0.41	0.64	0.66	0.65	0.20
EQMC	-0.61	-0.38	-0.55	-0.58	-0.63	-0.20
FWI	0.57	0.37	$\underline{0.66}$	$\underline{0.68}$	0.56	0.23

Table 2. The monthly mean weather variable or calculated index that has the most significant correlations with specified measures of monthly fire severity at each National Weather Service station and nearby National Forest for July during the years 1970 to 1983. The correlation coefficient is listed below the weather variable or index identifier.

NWS station and National Forest	Fire severity measure					
	Fires	Class C+ Fires	Acres	Costs	Fire Days	Class C+ Fire Days
Houghton Lake, MI Huron Manistee NF	FWI 0.43	T 0.63	PF 0.36	EQMC -0.35	FWI 0.59	T 0.63
International Falls, MN Superior NF	FWI 0.82	FWI 0.69	FWI 0.61	FWI 0.63	BI 0.78	W 0.64
Rapid City, SD Black Hills NF	PDI -0.84	PHI -0.65	FWI 0.66	FWI 0.68	PDI -0.91	PHI -0.54
Tallahasee, FL Apalachicola, NF	PDI -0.53	W -0.46	W -0.51	PDI -0.53	PF -0.52	T 0.35
Little Rock, AK Ouachita NF	BI 0.83	BI 0.68	BI 0.66	PHI -0.40	Z -0.77	BI 0.72
Missoula, MT Lolo NF	PDI -0.67	Z -0.78	Z -0.80	Z -0.76	RH -0.83	Z -0.81
Yakima, WA Wenatchee, NF	T 0.37	T 0.26	PF 0.51	PDI -0.43	PDI -0.46	PDI -0.26
Boise, ID Sawtooth NF	RH 0.42	PA -0.20	PA 0.40	T -0.41	T -0.25	PA -0.30
Medford, OR Rogue River NF	BI 0.56	PDI -0.51	W -0.31	PDI -0.61	BI -0.52	PDI -0.51
Salt Lake City, UT Wasatch NF	SPD 0.34	W 0.63	W 0.58	PF 0.44	SPD 0.67	W 0.62
Reno, NV Tahoe NF	BI 0.34	PF 0.49	PF 0.74	PHI -0.40	INT 0.53	PF 0.49
Albuquerque, NM Cibola NF	T 0.61	Z -0.51	INT 0.36	PA 0.38	PF 0.54	PF 0.50
Flagstaff, AZ Coconino NF	PHI -0.51	T -0.56	T -0.51	Z -0.37	Z 0.66	T -0.63
Los Angeles, CA Angeles NF	SPD 0.60	SPD 0.57	PDI 0.35	BI -0.34	PF -0.53	SPD 0.61

Figure 2 indicates the weather variables and indices most significantly related to July fire occurrence across the contiguous United States. The burning index (BI) of Chandler et al. (1983) most accurately predicts fires along the west coast. The Palmer Drought Index (PDI) is the most significant fire occurrence predictor from western Montana to the Dakotas. Florida fires are also significantly related to the PDI.

We looked at maps like Figure 2 for each month. For example, in January only the southernmost parts of California and the southeastern corner of the United States are in their fire seasons. In southern California, the Palmer Z-Index (Z) is the best predictor of fires. The BI is significant in Florida. In Arkansas, the PDI is the best predictor.

In April most of the Western United States still has winter weather. In southern California precipitation frequency (PF) is a good predictor of fire occurrence. Throughout the East, the BI is a good indicator of fires. In northern Minnesota PF and temperature are significant. No significant weather variables or indices were found for Michigan. In Arkansas, the FWI was significant.

By October the fire season in the High Plains has passed. In the Mississippi Valley, the Z-index is a good predictor of fires. Farther east the BI is signficant. Throughout the Rockies the BI is also the best predictor. In southern California, the Z-Index and PF are best.

Conclusions

Historical weather variables and indices, summarized by month, were a significant predictor of fire severity at many locations throughout the fire season. If monthly mean temperature, relative humidity, and precipitation frequency can be predicted accurately, between one-half and one-third of the next month's fire severity could then be anticipated.

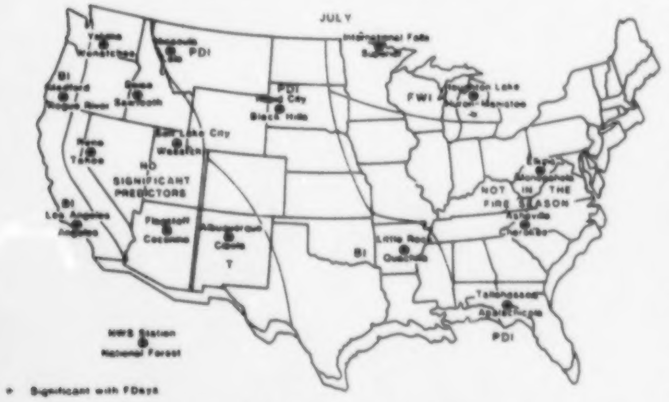


FIG. 2. Weather variables or calculated indices at National Weather Service stations that are most significantly related to fire occurrences on nearby National Forests in July. The significance level is arbitrarily set at 0.05.

We tabulated the significant weather variables and indices for each month at locations that were in fire season. We hoped to find a single weather variable, or perhaps two variables or indices, that could be used at all locations, in all months, to predict fire occurrence. What we found were striking east-west and north-south differences in almost all months. For example, in July the Burning Index (BI) most accurately predicted fires along the west coast, the Palmer Drought Index (PDI) was the most significant predictor from western Montana to the Dakotas, and further south in Arkansas the BI and in Florida the PDI were consistent predictors. Not only were there regional differences, but different weather variables or indices or both may be needed at the same location, at different times of the year. We found that in southern California in January the PDI is the best predictor of fires, in April precipitation frequency (PF) is a good predictor, in July it is the BI, and in October the Z-Index and PF are best.

Monthly mean windspeed usually was not a significant predictor for any of the fire measures at any time of the year for most locations. This is most likely because windspeed is too erratic to be used successfully as a monthly mean variable.

The simple linear models discussed are only the beginning of a long search for optimal, and perhaps nonlinear, predictive models that relate monthly mean weather variables and indices to monthly fire severity. The results shown here are sufficient to indicate that monthly fire prediction can be done and is a fruitful line of research.

References

BURGAN, R. E. AND R. A. HARTFORD. 1988. Computer mapping of fire danger and fire locations in the continental United States. J. For. 86:25-30.

CHANDLER, C., P. CHENEY, P. THOMAS, L. TRABAUD, AND D. WILLIAMS. 1983. Fire in Forestry. Vol I. John Wiley & Sons.

DEEMING, J. E., R. E. BURGAN, AND J. D. COHEN. 1977. The National Fire-Danger Rating System--1978. USDA For. Serv. Gen. Tech. Rep. INT-39. Intermountain For. Exp. Sta.

FISHER, W. C. AND C. E. HARDY. 1976. Fire-weather observers' handbook. USDA Forest Serv. Ag. Handbook 494. 152 p.

FLANNIGAN, M. O. AND J. B. HARRINGTON. 1987. A study of the relationship of meteorological variables to monthly provincial area burns. P. 229-234. In Proc. of the Conf. on Fire and Forest Meteor., San Diego, CA, Amer. Meteor. Soc.

FOSBERG, M. A. 1978. Weather in wildland fire management: the fire weather index. P. 1-4. In Proc. of the Conf. on Sierra Nevada Meteor., June 19-21, South Lake Tahoe, CA.

HAINES, D. A. AND V. J. JOHNSON. 1975. When are fires in season? Fire Manage. 17-23.

HAINES, D. A. AND W. A. MAIN. 1978a. Variation of six measures of fire activity associated with drought. P. 5-7. In Proc. Fifth National Conf. on Fire and For. Meteor., Atlantic City, NJ. Amer. Meteor. Soc.

HAINES, D. A., W. A. MAIN, AND E. F. MCNAMARA. 1978b. Forest fires in Pennsylvania. USDA For. Serv. Res. Paper NC-158, North Central For. Exp. Sta.

KLEIN, W. K. AND B. T. WHISTLER. 1989. Specification of monthly mean anomalies of fire weather elements from concurrent anomalies of the mean 700 mb height field. In Proc. 10th Conf. on Fire and For. Meteor. April 17-21. Ottawa, Ontario.

NELSON, R. M. 1964. The National Fire Danger Rating System. USDA For. Serv. Res. Paper SE-13. Southeastern For. Exp. Sta.

PALMER, W. C. 1965. Meteorological drought. Weather Bureau Research Paper No. 45, U.S. Dept. of Commerce, Washington, DC.

SIMARD, A. J. 1968. The moisture content of forest fuels. I. A review of the basic concepts. For. Fire Res. Inst. Inf. Rep. FF-X-14.

The Application of a Micro-Computer Based System to Fire Weather Support

B.J. SNYDER
Arctic Weather Centre
Edmonton, Alberta

Abstract

Each summer the Arctic Weather Centre (ArWC) seconds a meteorologist to the Territorial Forest Fire Centre (TFFC) in Fort Smith, N.W.T. The primary duties of the forestry meteorologist include briefing forestry personnel on weather over the Mackenzie district of the N.W.T., and preparation of an afternoon forestry forecast.

This past summer saw the installation of MODS (Meteorological Services Research Branch (MSRB) Operational Display System), a graphics display system designed to meet the general requirements of a weather office.

This paper outlines the features of MODS and discusses current and future applications to the fire weather program in Fort Smith.

Résumé

Chaque été, le Centre météorologique de l'Arctique (CMAR) fourmit un météorologiste au Centre forêt-météo territorial (CFMT) sis à Fort Smith, T.N.-O. Dans l'exercice de ses fonctions primaires, le météorologiste forestier doit, entre autres, informer le personnel forestier du temps actuel et prévu du district du Mackenzie des T.N.-O. En outre, on prépare pour le district une prévision d'après-midi pour la foresterie.

L'été decoier, on a mis en oeuvre le système VEM (système d'affichage opérationnel de la Direction de la recherche sur les services météorologiques (DRSM), un système d'affichage graphique rencontrant les exigences d'un bureau météorologique. Ce système complète d'une façon très utile le poste de travail du météorologiste forestier. Le document présente les caractéristiques du système VEM et disuite de l'utilisation courante et future au programme forêt-météo à Fort Smith.

Introduction

The Arctic Weather Centre (ArWC) is the only office in Canada to offer the dedicated on site services of a meteorologist to a forestry centre. From mid-May to mid-August of each year, a meteorologist is seconded to the Territorial Forest Fire Centre (TFFC) in Fort Smith, Northwest Territories (NWT).

Last summer, the TFFC installed a micro-computer based workstation. This paper outlines the components of this system and discusses its present and future application to fire weather support.

Background

Up until the summer of 1988, the forecaster in Fort Smith had limited guidance material at his/her disposal; weather charts were received on an analog facsimile machine and teletype traffic was available from one circuit. In the absence of a plotter, surface analyses and tephigrams had to be prepared by hand...a time consuming task. Indeed, there was little time available to consider the meteorological content of forecasts received from the ArWC; essentially, the meteorologist acted as a briefer to forestry personnel and made minor adjustments to the fire weather forecasts issued by the ArWC. What was needed was a field workstation to enable the forecaster to access data normally available to ArWC personnel, and to automate the plotting of charts. Such a system would allow for more time to analyse data and to produce the afternoon fire weather forecast.

The MSRB Operational Display System (MODS) developed by the Meteorological Services Research Branch (MSRB) of Atmospheric Environment Service met the above requirements. Similar systems had been used for weather support during the Canadian Atlantic Storms Project (CASP) and the 1988 Calgary Olympics. The TFFC consequently purchased the necessary components for such a workstation for the 1988 fire season. This system paved the way for a tremendous expansion in data available to the forecaster and the potential to greatly improve the fire weather support provided to the TFFC.

Features of MODS

MODS was designed as a graphics display system to meet the general requirements of a weather office. Hardware consists of an IBM-AT compatible microcomputer with a high resolution display. Communication hardware consists of an internal modem to the HP1000 computer in Edmonton. Hard copies are

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

obtained via an HP7475 pen plotter and a dot matrix printer.

The system runs under the Disk Operating System (DOS) and is organized into three main directories (1):

```
...Mods     --------Comm
            --------Ras
            --------Util

...Met      --------
            --------etc.

...Metag
```

The first directory, Mods, is the active directory containing the control files for MODS (e.g. to control the menus, the display, the communications programs and necessary files, etc). The Met directory is used for computer 'book-keeping'. The Metag directory is for the graphics library.

The screen is conveniently split into two sections, the display area and the menu area. Interaction with MODS is accomplished via a menu system using the directional arrow keys for navigation.

Hard and soft copies are available for the following (see Figures 1 to 4 for examples):

Surface plots and upper air plots
Temperature/moisture profiles and wind profiles (with height)

It is worth mentioning that the system used for the Olympics in Calgary had a high speed modem to communicate with the CYBER computer in Montreal. This enabled forecasters to obtain additional images such as surface and upper air prognostic charts as well as calculated fields and wind models. It is hoped that the system in Fort Smith will eventually be able to take advantage of some of the programs being developed in Edmonton and other weather centres to obtain additional images.

Forestry Forecast Support to Fort Smith

Beginning in early May of each year, the ArWC issues an early morning and an afternoon fire weather forecast for the NWT forestry districts. These forecasts contain elements of temperature, relative humidity, wind and precipitation. Forecasts are sent out on teletype to AES users and also sent via telefax to the TFFC for dissemination to forestry district offices.

The implementation of MODS last year allowed the Fort Smith meteorologist to take over the preparation and issue of the afternoon fire weather forecast. The addition of MODS also allowed for access to much more data than before, including 1-5 day temperature forecast guidance, Model Output Statisitics (MOS) and calculated stability indices. Acquisition of this data helped a great deal in preparing for comprehensive morning weather briefings to the duty officer and other forestry personnel.

Along with the afternoon issue of the fire weather forecast, the meteorologist also provided forecast values of 1300h MDT temperature and relative humidity for each forestry district as inputs to the FFPS (Forest Fire Preparedness System). Again, access to numerical temperature guidance through MODS proved very useful.

The Future

The full potential of MODS as a field workstation for forest meteorology has yet to be realized. Having only been operational for less than one summer, it is not surprising that there are some bugs still in the system.

A dedicated line to Edmonton via Yellowknife instead of the dial up system now in place will increase time savings and convenience.

Eventually, forestry weather reports will be input through computers. This will certainly aid the fire weather forecaster as it will allow the MODS workstation to plot this data and perform manipulations such as calculating representative areal temperatures, relative humidities, indices etc. With the MODS now in place, numerous software programs (such as mixing height forecasts, climate summaries and model output statistic forecasts) can be implemented to improve the scale and type of forecasts that the meteorologist can produce.

Through the use of a laptop computer equipped with a modem, the MODS could prove to be an extremely valuable tool for meteorologists who are required to prepare on-site forecasts at a fire.

Conclusions

The implementation of MODS proved to be an indispensible tool to the fire weather forecasting program in Fort Smith. Not only did it increase the efficiency of the forecaster's production, but it also made available much more data and guidance material, thereby increasing the forecaster's effectiveness.

It is generally regarded that the utility of meteorological service is enhanced by having a forecaster colocated with the user. Most forestry centres rely on the services of a meteorologist at an AES weather centre, removed from the day-to-day activities of the fire centre. In contrast, the TFFC has a meteorologist on site. In the past, however, the full potential of the forecaster was not realized due to limitations on available forecast facilities. The addition of MODS has created a work station closely resembling one found in a weather centre. Thus, I believe that the TFFC has the best of both worlds: close contact with a meteorologist and a state-of-the-art forecasting workstation.

References

1. Report on Weather Support for the 1988 Calgary Olympics, 1988. Unpublished.

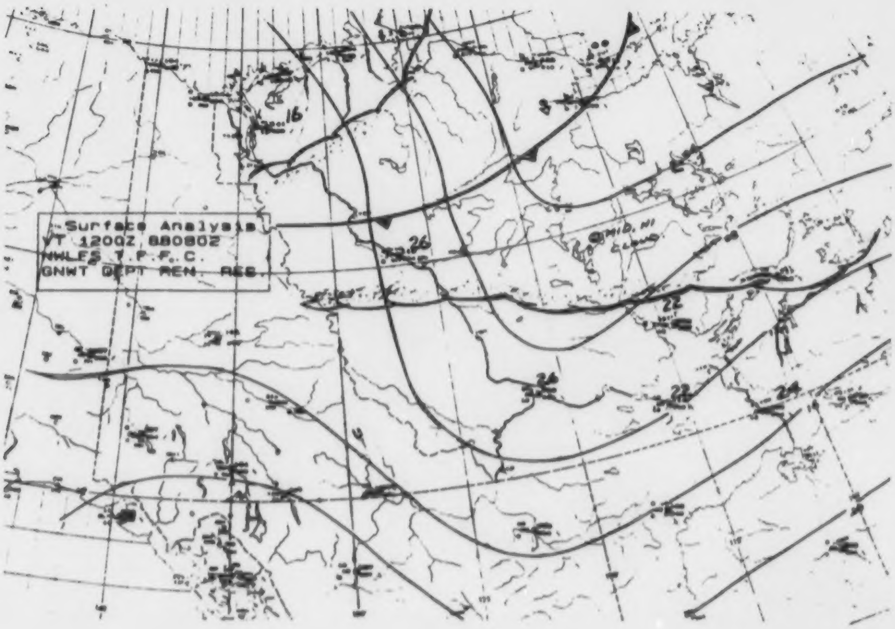

Surface Analysis
VT 1200Z 880802
NWLFS T.F.F.C.
GNWT DEPT REN. RES.
16
26
22
24
22
24

FIG. 1 Suface Plot from MODS

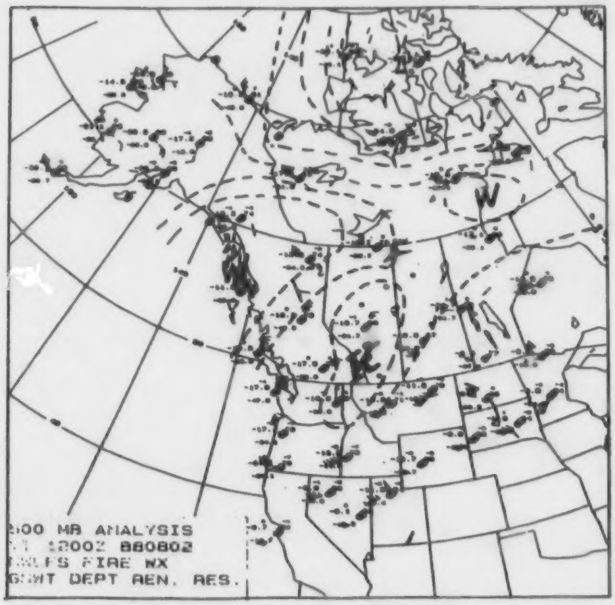

500 MB ANALYSIS
VT 1200Z 880802
NWLFS FIRE WX
GNWT DEPT REN. RES.

FIG. 2. 500 mb Plot from MODS

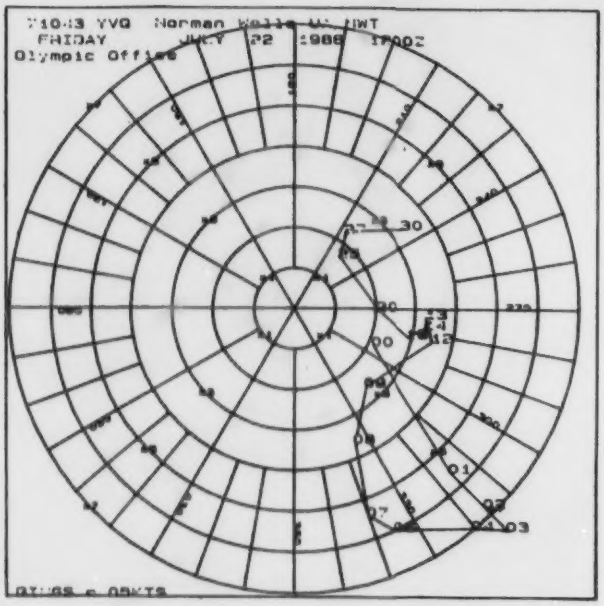


FIG. 3. Hodograph Produced by MODS

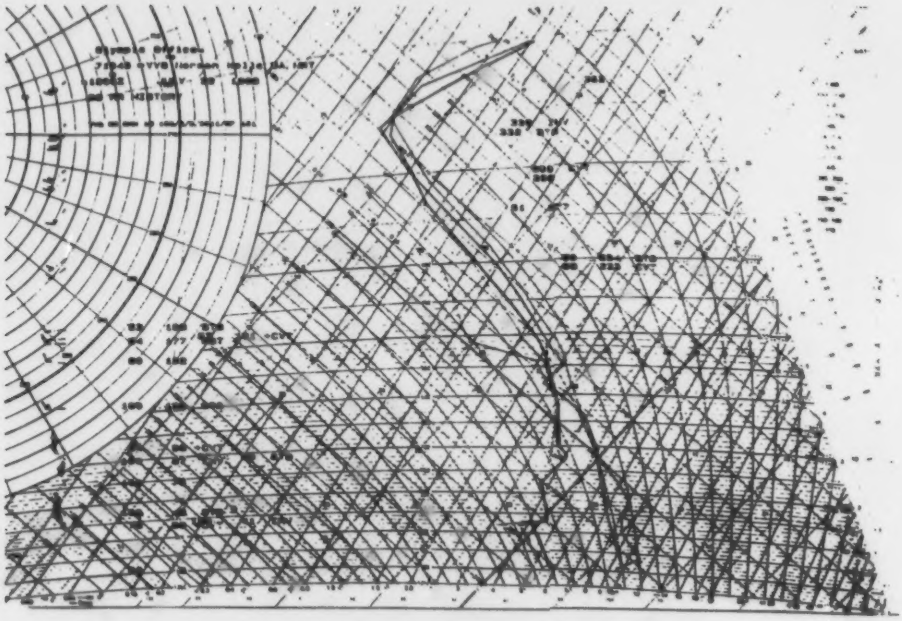


FIG. 4 Tephigram Produced by MODS

Fire Weather Forecast Program

R. WINTERER
Alberta Weather Centre
Edmonton, Alta.

Abstract

The Alberta Weather Centre (ALWC) of the Atmospheric Environment Service, Environment Canada, provides meteorological support to the British Columbia Forest Service (BCFS) and the Forest Management Division of Parks Canada. The forecasts for the BCFS provide forecast information for northeastern British Columbia: west of the 120th longitude and east of the Continental Divide. Support to Parks Canada is provided for the Jasper, Banff and Waterton National Parks.

Daily forecasts of temperature, relative humidity and wind speed and direction are prepared in support of ongoing fire control operations and used to calculate various indices. The bulletins also contain forecasts of probabilities of any, and of 2 mm of precipitation; as well as probabilities of any, and intense lightning.

Fire weather forecasts during the summer of 1988 were prepared for the period May to September. Verification of forecast parameters was undertaken to assess ALWC's accuracy and to identify any weaknesses in the program that need improvement. This paper presents some verification results and illustrates the team effort played by the Prognostician, the Severe Weather Forecaster and the Public Forecaster in generating this forecast product.

Résumé

Le Centre météorologique de l'Alberta (Service de l'environnement atmosphérique, Environment Canada) apporte une aide en matière de prévisions météorologiques au Service des forêts de la Colombie-Britannique et à la Division de l'aménagement forestier de Parcs Canada. Les bulletins destinés au Service des forêts de la Colombie-Britannique fournissent des prévisions pour la partie nord-est de la Colombie-Britannique, à l'ouest de 120° de longitude et à l'est de la ligne continentale de partage des eaux. Les prévisions destinées à Parcs Canada sont pour les parcs nationaux de Jasper, de Banff et de Waterton.

Des prévisions quotidiennes de la température, de l'humidité, et du ventsont préparées pour appuyer les opérations permanentes de protection des forêts contre le feu et pour calculer divers indices. Les bulletinsmétéorologiques contiennent également des prévisions de probabilités d'occurrence de précipitations (de moins ou de plus de 2 mm) et de la foudre (intense ou non).

Des prévisions forêt-météo au cours de l'été 1988 ont été préparées d'avril à octobre. Une vérification des paramètres de prévision a été entreprise pour évaluer l'exactitude du programme du Centre météorologique de l'Alberta et pour identifier toute faiblesse qui aurait besoin d'être améliorée. Cet article présente certains résultats de cette vérification et illustre les efforts collectifs déployés par le prognosticien, le spécialiste du temps dangereux et le prévisionniste affecté au poste public pour produire ce type de prévision.

Forecast Program

NORTHEASTERN BRITISH COLUMBIA

The forecasts were issued seven days per week at 6:30 AM mountain daylight time (MDT). Forecast parameters were valid at 1:00 PM local daylight time (LDT). A second forecast issued at 11:45 AM MDT was used for planning purposes as the parameters were valid at 1:00 PM LDT on the next day. This release was issued on Monday to Friday only. The format of all bulletins was identical, containing a synopsis, forecast temperatures, humidities, wind direction, wind speed, probabilities of measurable precipitation, probabilities of 2.0 mm or more of precipitation, probabilities of any lightning and the probabilities of intense lightning. The synopsis described the expected development and motion of major weather features over the next 5 days. Forecasts of temperature, humidity and winds were provided for the Fort Nelson, Chetwynd and Fort St John; Zones 10, 11 and 29 (Figure 1). The valid period for the probabilities of precipitation and lightning was noon to midnight LDT.

JASPER, BANFF AND WATERTON NATIONAL PARKS

The forestry forecasts were issued once per day seven days per week at 11:30 AM LDT for the entire fire season and were valid for the Jasper, Banff and Waterton National Parks. This bulletin was identical to the one prepared for Northeastern British Columbia but the parameters were valid at 1:00 PM LDT on the next day.

Assessment Procedures

The BCFS and Parks Canada agreed that predicted forecast elements for the regions would be verified

---

Presented at the 10th Conference on Fire and Forest Meteorology, April 17-21, 1989, Ottawa, Canada.

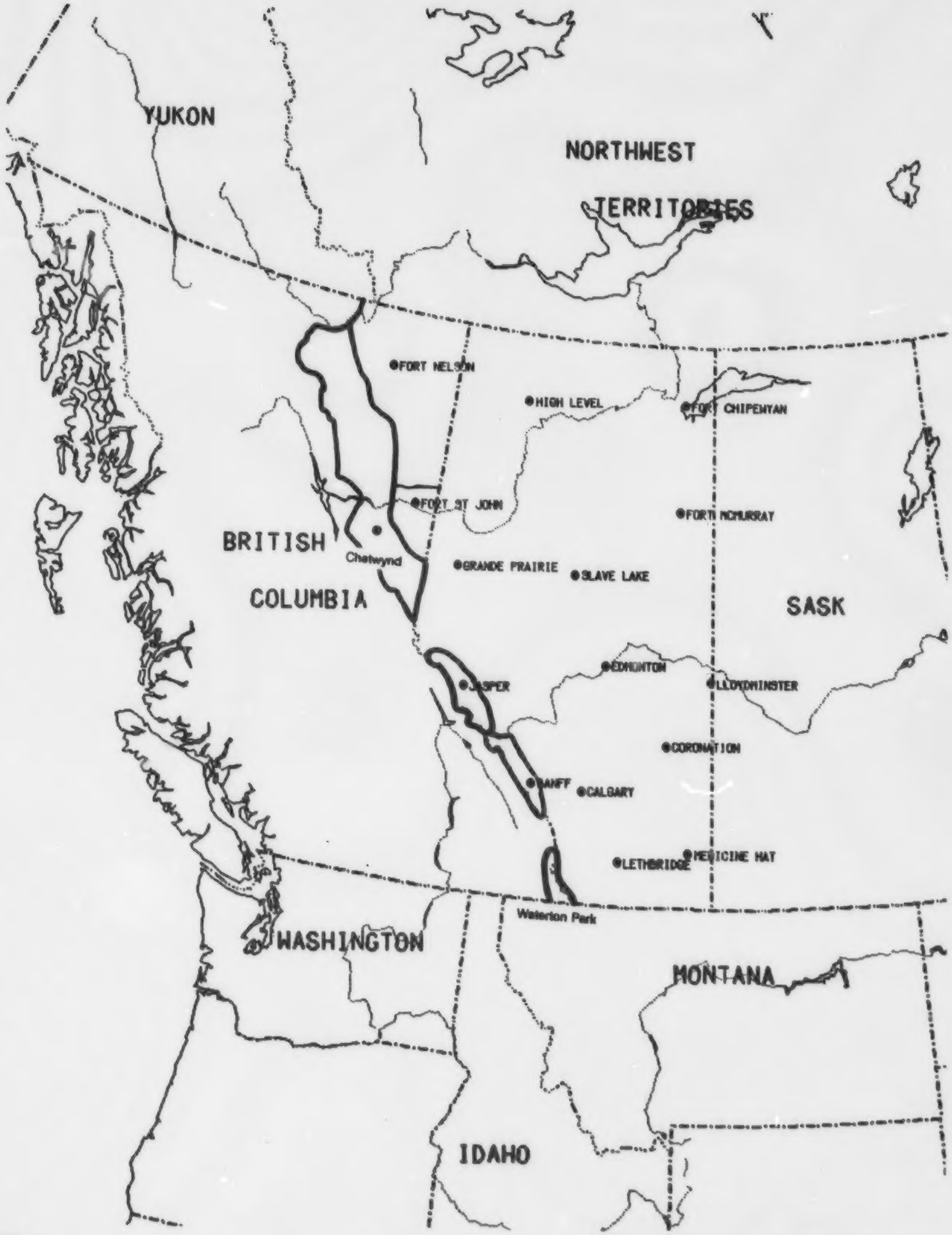

YUKON
NORTHWEST
TERRITORIES
FORT NELSON
HIGH LEVEL
FORT CHIPEWYAN
FORT ST JOHN
FORT MCMURRAY
BRITISH
COLUMBIA
Chetwynd
GRANDE PRAIRIE
SLAVE LAKE
SASK
JASPER
EDMONTON
LLOYDMINSTER
CORONATION
BANFF
CALGARY
LETHBRIDGE
MEDICINE HAT
Waterton Park
WASHINGTON
MONTANA
IDAHO

FIG. 1

against observations received from valid observation sites within each region. Consequently forecasts for and observational data from Fort Nelson (YYE), Fort St John (YXJ), Chetwynd (YCQ), Jasper (WJA) and Banff (WBA) could be compared and used to calculate verification statistics. Insufficient weather data was available from Waterton Park to permit any objective assessment of the forecasts.

TEMPERATURE AND HUMIDITY

All forecasts, both the early morning and late morning issues of temperature and humidity were compared against the 1:00 PM LDT observations from the five sites for the period June 1 to September 30, 1988. Calculations produced the Mean Bias, Mean Absolute Error and Percentage of forecasts within 3 and 5°C, respectively. Relative Humidity was similarly analysed to calculate Mean Bias, Mean Absolute Error and Percentage of forecasts within 15 and 25 percent, respectively. (Table 1)

WIND DIRECTION AND SPEED

Forecast and observed wind direction and speed were compared using three conditional tests with results presented in Table 1.

a) If the Observed and Forecast Winds were greater than 15 km/h, then Directional Error is "Forecast Direction" minus the "Observed Direction" and the Speed Error is the "Forecast Speed" minus the"Observed Speed".

b) If the Forecast Wind Speed was less than or equal to 15 km/h, then No directional error is assigned as this is considered to be a light and variable wind condition.

If the observed wind speed is less than or equal to 15 km/h - No Error. If the observed wind speed is greater than 15 km/h - Speed Error is 15 minus the Observed Wind Speed.

c) If the Observed Wind Speed is less than or equal to 15 km/h, then No directional error is assigned as this is considered to be a light and variable wind condition.

If the forecast wind speed is less than or equal to 15 km/h - No Error. If the forecast wind speed is greater than 15 km/h - The error is forecast wind speed minus 15.

PROBABILITIES OF PRECIPITATION (PoP)

Probabilities of Precipitation were forecast in a range from 0 to 100% and were considered to be valid for the period 12 Noon to Midnight (LDT). The reliabilities, as calculated, are defined as the ratio of the number of forecasts with precipitation versus the total number of forecasts of a given PoP. Forecasts were provided for two categories; measurable (≥0.2 mm), as well as 2.0 mm or more of precipitation. As the number of events resulting in 2.0 mm or more of precipitation were statistically insignificant, only results for measurable precipitation are presented in Table 2.

PROBABILITIES OF LIGHTNING

Two categories of lightning were considered in the forecast program. The first was any lightning, consisting of one or more lightning strikes in a region. The second was intense lightning, defined as 30 or more lightning strikes within a 60 mile square area. Lightning data was extracted from plots provided by the BCFS and from the lightning detection system (linked to the Alberta Forest Service's system) in place at the Alberta Weather Centre. The number of events which constituted intense lightning were so few that no statistically reliable results could be reached. Table 2 provides calculations regarding the probabilities of any lightning.

Results and Conclusions

FORECAST GENERATION

Forestry forecasts at the ALWC are the result of a team effort. The team consists of a Severe Weather Forecaster (concentrating on the expected convective activity), a Prognostician (concentrating on the expected movement of synoptic weather patterns) and the Public Forecaster who concentrates on forecasting temperature, humidity and cloud conditions. The combined expertise of these three forecasters is brought together to produce the Forestry Forecasts.

TEMPERATURE FORECASTS

The temperature forecasts were quite accurate with only a slight negative Mean Bias of 0.73°C. The Mean Absolute Error of between 2.3 and 3.0 is considered quite small and is, in the author's opinion, "state of the art".

RELATIVE HUMIDITIES

Relative Humidities were slightly overforecast with a Mean Bias of 0.84%. The MAE of 12.50% is quite representative for all stations and no particular deviations were noted.

WIND DIRECTIONS

Forecasts of wind directions tended to have a slight negative Bias. The predicted wind directions for Chetwynd however have had a very strong positive bias which in the author's opinion is due to local topography. The strong positive Bias is not expected to have been representative for the entire region and the utility of the wind direction forecasts at Chetwynd is expected to have been high. Differing experiences or opinions are solicited to help confirm this conclusion.

Table 1. Temperature, Relative Humidity, Wind Direction and Wind Speed Verification Results of the 1988 Alberta Weather Centre's Forestry Forecasts.

	WBA Banff	WJA Jasper	YXJ Fort St John	YCQ Chetwynd	YYE Fort Nelson	Average
Temperature (°C)						
Mean Bias	-0.67	-0.49	-0.55	-1.26	-0.68	-0.73
Mean Abs Error	2.99	2.74	2.32	2.69	2.71	2.69
% Error ≤ 3°	68.22	67.25	75.37	70.94	67.70	69.90
% Error ≤ 5°	89.09	89.81	94.08	88.11	88.01	89.82
Relative Humidity (%)						
Mean Bias	4.18	2.11	-2.73	2.34	-1.72	0.84
Mean Abs Error	11.42	13.70	12.58	12.82	11.96	12.50
% Error ≤ 15%	80.77	71.62	72.67	74.41	80.05	75.91
% Error ≤ 25%	92.49	84.98	85.43	89.20	91.79	88.78
Wind Direction (Degrees)						
Mean Bias Deg	-3.11	1.39	-4.70	24.54	-4.10	2.80
Mean Abs Error	37.80	49.19	38.73	59.31	54.27	47.86
% Error ≤ 45°	72.33	61.02	78.39	44.82	60.15	63.34
% Error ≤ 90°	82.44	79.45	89.62	78.61	75.77	81.18
Wind Speed (km/h)						
Mean Bias	1.02	2.26	0.29	2.14	1.29	1.40
Mean Abs Error	6.29	5.75	8.29	9.15	6.87	7.27
% Error ≤10 km/h	82.41	80.86	65.68	61.30	77.84	73.62
% Error ≤15 km/h	95.94	98.30	88.64	79.04	92.29	90.84

Table 2. Reliabilities of the 1988 Alberta Weather Centre Probability of Precipitation and Probability of Lightning Forecasts.

	WBA Banff	WJA Jasper	YXJ Fort St John	YCQ Chetwynd	YYE Fort Nelson	Average
Reliabilities of Probabilities of Measurable Precipitation (≥ 0.2 mm)						
≤10%	8.57%	8.85%	1.04%	0.00%	0.00%	3.69%
20%	27.50%	26.65%	7.72%	3.57%	21.11%	17.31%
30%	23.33%	0.00%	42.50%	23.96%	15.83%	21.13%
40%	44.17%	47.62%	19.44%	22.82%	31.89%	33.19%
50%	50.00%	100.00%	25.00%	50.00%	0.00%	45.00%
60%	58.33%	45.83%	23.33%	44.79%	86.11%	51.68%
70%	41.67%	50.00%	25.00%	0.00%	65.28%	36.39%
80%	100.00%	50.00%	25.00%	12.50%	64.58%	50.42%
90%	100.00%	83.33%	100.00%	0.00%	83.33%	73.33%
100%	75.00%	33.33%	62.50%	41.67%	75.00%	57.50%
Reliabilities of Probability of any Lightning						
≤10%	19.28%	23.53%	24.95%	35.83%	40.94%	28.90%
20%	33.33%	39.29%	28.47%	45.21%	54.17%	40.09%
30%	58.33%	31.25%	52.08%	70.00%	62.50%	54.83%
40%	12.50%	83.33%	15.97%	51.39%	50.00%	42.64%
50%	n/a	n/a	50.00%	100.00%	0.00%	50.00%
60%	100.00%	55.56%	19.38%	58.33%	90.28%	64.71%
70%	50.00%	100.00%	91.67%	75.00%	100.00%	83.33%
80%	50.00%	50.00%	50.00%	95.83%	91.67%	67.50%
90%	n/a	n/a	25.00%	75.00%	100.00%	66.67%
100%	100.00%	100.00%	25.00%	75.00%	83.33%	76.67%

WIND SPEED

Wind speeds for all stations were slightly overforecast with a positive Bias of 1.40 km/h. The MAE ranged from 5 to 7 km/h; with significant overforecasting at Chetwynd and Fort St John. At Chetwynd, since the direction bias is strong also, it is concluded that the local topography and friction are backing the wind direction and reducing the wind speed. At Fort St John, forecasters tended to expect weak chinook type winds which quite often did not occur. Efforts will be made to counter this tendency during the next fire season.

RELIABILITIES OF PRECIPITATION FORECASTS

Figure 2 illustrates the reliabilities of the precipitation forecasts (measurable amounts) achieved for all stations during the season. On average it can be seen that the predicted probabilities were about 10 to 20 percent underforecast, with the greatest errors noted at 70% and higher values. It was noted during the assessment procedure that when high PoPs were used some precipitation usually occurred somewhere in the region though not necessarily at the observing site.

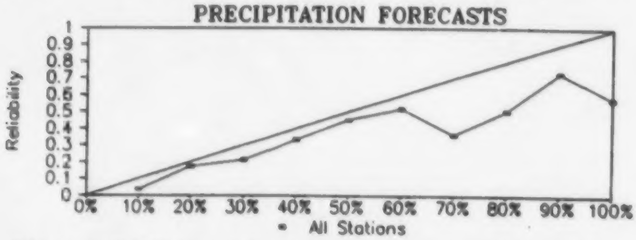


FIG 2. Reliabilities of Precipitation Forecasts (Measurable Amounts)

RELIABILITIES OF LIGHTNING FORECASTS (PoL)

Figure 3 illustrates the reliabilities of forecasts of any lightning for the stations in the National Parks and in Northeastern British Columbia. At predicted probabilities of less than 50% the predicted PoL is on average about 10 to 20% too low. The number of days/events with PoL greater that 50% was quite small and statistical inferences which can be made from this data base are suspect.

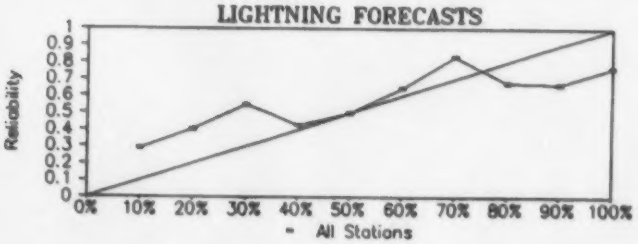


FIG 3. Reliabilities of Any Lightning

References

VANDEVYVERE, D. 1988. The 1987 Northwestern Ontario Forestry Program. Central Region Technical Note, 88-4.

Opening Remark Speakers (From Left to Right):

Mr. Jean Claude Mercier - Deputy Minister, Forestry Canada,
351 St. Joseph Boulevard, Hull, Quebec K1A 1G5

Mr. Howard Ferguson - Assistant Deputy Minister
(Currently Ms. E. Dowdeswell)
Atmospheric Environment Service, Environment Canada
4905 Dufferin Street, Downsview, Ontario M3H 5T4

Mr. Bob Burgar - Assistant Deputy Minister for Southern Ontario,
Ontario Ministry of Natural Resources
2nd Floor, Building 13, R.R.#2, Maple, Ontario L0J 1E0

Mr. Regis Proulx - Chief, Service de la Protection Contre le Feu
Ministère de L'Energie et des Ressources du Québec
1530 Blvd. de l'entente, Québec City, Québec G1S 4S7

Author's Addresses/Addresses des auteurs

(1) Martin E. Alexander
Fire Research Officer
Northern Forestry Centre
Forestry Canada
5320-122 Street
Edmonton, Alberta
T6H 3S5

(2) Kerry R. Anderson
Northern Forestry Centre
Forestry Canada
5320-122 Street
Edmonton, Alberta
T6H 3S5

(3) Patricia L. Andrews
Mathematician
United States Department of Agriculture
Intermountain Fire Sciences Laboratory
P.O. Box 8089
Missoula, MT. 59807
U.S.A.

(4) Barry B. Aronovitch
National Weather Service Office
Fire Weather
c/o Department of Natural Resources PY-19
Olympia, Washington 98504
U.S.A.

(5) L.R. Barber
U.S. Department of Agriculture
Forest Service
Southwestern Forest Experiment Station
Route 1, Box 182A
Dry Branch, GA 31020
U.S.A.

(6) Larry F. Bednar
Forest Fire Laboratory
Pacific Southwest Forest and
Range Experiment Station
Forest Service
US Department of Agriculture
4955 Canyon Crest Drive
Riverside, CA 92507
U.S.A.

(7) Gordon D. Booth
U.S. Forest Service
Intermountain Research Station
Intermountain Fire Science Laboratory
Ogden, Utah
U.S.A.

(8) Dave Branson
Queen's University
Department of Geography
Kingston, Ontario
K7L 3N6

(9) James K. Brown
USDA Forest Service
Intermountain Research Station
P.O. Box 8089
Missoula, MT 59807
U.S.A.

(10) Robert E. Burgan
Southeastern Forest Experiment Station
Route 1, Box 182A
Dry Branch, GA 31020
U.S.A.

(11) B. Burke
Aviation and Fire Management
Northern Region Service Centre
R.R. #2
Timmins, Ontario
P4N 7C2

(12) Jean-Pierre Carpentier
Service de la recherche appliqué
Ministère de l'Engerie et des Ressources
du Québec
2700 Einstein
Sainte-Foy, Québec
G1P 3W8

(13) Wayne G. Clowater
Forest Fire Protection Branch
N.B. Department of National Resources
and Energy
498 York Street
Fredericton, N.B.
E3B 3P7

(14) W.B. Cohen
Colorado State University
Forest and Wood Sciences
Fort Collins, Colorado 80523
U.S.A.

(15) Bernadette H. Connell
USDA Forest Service
Rocky Mountain Forest and
Range Experiment Station
240 West Prospect
Fort Collins, CO 80526-2098
U.S.A.

(16) Marie R. Coyea
Université Laval
Faculté de Foresterie et de Geodesie
Pavillon Vachon Cite Universitaire
Ste. Foy, Québec
G1K 7P4

(17) Nancy A. Dean
Office of Agricultural and
Fire Weather
National Weather Service, NOAA
University of California
Riverside, CA 92521-0311
U.S.A.

(18) G. Debarr
US Department of Agriculture
Forest Service
Southwestern Forest Experiment Station
Route 1, Box 182 A
Dry Branch, GA 31020
U.S.A.

(19) William J. DeGroot
Fire Research Officer
Forestry Canada
101-15 St. East
Prince Alberta, Saskatchewan
S6V 6G1

(20) James E. Eenigenburg
U.S. Forest Service
1407 South Harrison Road
East Lansing, MI 48823
U.S.A.

(21) J.C. Feller
Faculty of Forestry
University of B.C.
Vancouver, B.C.
V6T 1W5

(22) J. Feunekes
R/EMS Research Ltd.
P.O. Box 651
Fredericton, N.B.
E3B 5A6

(23) William C. Fisher
Intermountain Science Laboratory
Intermountain Research Station
USDA Forest Service
P.O. Box 8089
Missoula, MT 59807
U.S.A.

(24) Michael Flannigan
Forestry Canada
Petawawa National Forestry Institute
P.O. Box 2000
Chalk River, Ontario
K0J 1J0

(25) Val E. Fletcher
Planning, Development,
and Research Section
Forest Protection Branch
British Columbia Ministry of Forests
31 Bastion Square
Victoria, BC
V8W 3E7

(26) Douglas G. Fox
USDA Forest Service
Rocky Mountain Forest and
Range Experiment Station
240 West Prospect
Fort Collins, CO. 80256-2098
U.S.A.

(27) William H. Frandsen
Research Physicist
United States Department of Agriculture
Forest Service
Intermountain Research Station
P.O. Box 8089
Missoula, MT 59807
U.S.A.

(28) Francis M. Fujioka
Forest Fire Laboratory
Pacific Southwest Forest and
Range Experiment Station
Forest Service, USDA
Riverside, CA 92507
U.S.A.

(29) Richard Gilbert
Meteoglobe Canada Inc.
Roxboro, Québec

(30) Armando González-Cabán
Forest Fire Laboratory
Pacific Southwest Forest and
Range Experiment Station
USDA, Forest Service
4955 Canyon Crest Drive
Riverside, CA 92507
U.S.A.

(31) Sallie Gordon
College of Letters and Science
Department of Psychology
University of Idaho
Moscow, Idaho 83843
U.S.A.

(32) Stephen K. Grimaldi
Planning, Development, and Research Section
Forest Protection Branch
British Columbia Ministry of Forests
31 Bastion Square
Victoria, B.C.
V8W 3E7

(33) Tom Grimes
Centre de Transfert
Technologique de Maniwaki
Aéroport de Maniwaki
C.P. 50
Maniwaki, Québec
J9E 3B3

(34) J. Guenette
Centre de Transfert
Technologique de Maniwaki
Aéroport de Maniwaki
C.P. 50
Maniwaki, Québec
J9E 3B3

(35) James B. Harrington
Forestry Canada
Petawawa National Forestry Institute
P.O. Box 2000
Chalk River, Ontario
K0J 1J0

(36) Michael G. Harrington
Research Forester
USDA, Forest Service
Intermountain Research Station
P.O. Box 8089
Missoula, MT 59807
U.S.A.

(37) Roberta A. Hartford
Intermountain Research Station
Forest Service, USDA
P.O. Box 8089
Missoula, Montana 59807
U.S.A.

(38) Brad C. Hawkes
Fire Research Unit
Pacific Forestry Centre
506 West Burnside Road
Victoria, BC
V8Z 1M5

(39) Kelvin G. Hirsch
Fire Research Officer
Manitoba District Office
Forestry Canada
104-180 Main Street
Winnipeg, Manitoba
R3C 1A6

(40) Roger D. Hungerford
Intermountain Fires Sciences Lab.
USDA Forest Service
P.O. Box 8089
Missoula, MT 59807
U.S.A.

(41) Jin Ji-Zhong
Heilongjiang Forest Protection Institute
Hapin Road No. 7, Harbin City
People's Republic of China

(42) R. W. Johansen
Centre de Transfert
Technologique de Maniwaki
Aéroport de Maniwaki
C.P. 50
Maniwaki, Québec
J9E 3B3

(43) William H. Klein
Cooperative Institute for Climate Studies
Department of Meteorology
University of Maryland
College Park, MD 20742
U.S.A.

(44) Yordan Kurpanov
Expert Forestier
Consultant AFIF
"Les Complect"
17, rue Antime I
1303. Sofia
Bulgarie

(45) Richard A. Lanoville
Territorial Forest Fire Centre
Department of Renewable Resources
Government of the N.W.T.
Box 7, Fort Smith, N.W.T.
X0E 0P0

(46) Don Latham
Intermountain Fire Sciences Laboratory
U.S. Forest Service
P.O. Box 8089
Missoula, MT 59807
U.S.A.

(47) Bruce D. Lawson
Head, Fire Research Unit
Forestry Canada
Pacific Forestry Centre
506 W. Burnside Road
Victoria, B.C.
V8Z 1M5

(48) Brian S. Lee
Fire Research Officer
Forestry Canada
Northern Forestry Centre
5320 - 122nd Street
Edmonton, Alberta
T6H 3S5

(49) V.J. Lieffers
Department of Forest Science
University of Alberta
Edmonton, Alberta
T6G 2H1

(50) Tim J. Lynham
Forest Fire Research Officer
Great Lakes Forestry Centre
P.O. Box 490, 1219 Queen St. E.
Sault Ste. Marie, Ontario
P6A 5M7

(51) Don C. MacIver
Canadian Climate Centre
Atmospheric Environment Service
Environment Canada
4905 Dufferin Street
Downsview, Ontario
M3H 5T4

(52) William A. Main
US Forest Service
1407 South Harrison Rd
East Lansing, MI 48823
U.S.A.

(53) E. Manchester
US Department of Agriculture
Forest Service
Southwestern Forest Experiment State
Route 1, Box 182 A
Dry Branch, GA 31020
U.S.A.

(54) David L. Martell
Faculty of Forestry
University of Toronto
203 College Street
Toronto, Ontario
M5S 1A1

(55) Michael Matson
NOAA, National Environmental Satellite,
Data and Information Service
E/SP22, mail stop H
Washington, DC 20233
U.S.A.

(56) William M. Mawdsley
Department of Renewable Resources
Government of the Northwest Territories
Box 390
Fort Smith, N.W.T.
X0E 0P0

(57) Robert S. McAlpine
Fire Research Officer
Northern Forestry Centre
Forestry Canada
5320-122 Street
Edmonton, Alberta
T6H 3S5

(58) Morris H. McCutchan
Pacific Southwest Forest and Range
Experiment Station, Forest Service
U.S. Department of Agriculture
Riverside, CA 92507
U.S.A.

(59) Douglas J. McRae
Forestry Canada
Great Lakes Forestry Centre
P.O. Box 490
Sault Ste. Marie, Ontario
P6A 5M7

(60) Ian R. Methven
R/EMS Research Ltd.
P.O. Box 651
Fredericton, N.B.
E3B 5A6

(61) Glen A. Morris
Intermountain Fire Sciences Lab.
USDA Forest Service
P.O. Box 8089
Missoula, MT 59807
U.S.A.

(62) Henry Newhouse
National Weather Service
Silver Spring, MD 20910
U.S.A.

(63) Charles V. Nilsson
Pacific Southwest Forest and Range
Experiment Station
USDA Forest Service
Riverside Fire Laboratory
4955 Canyon Crest Drive
Riverside, CA 92507
U.S.A.

(64) Nicholas Nimchuk
Fire Weather Meteorologist
Alberta Forest Service
Provincial Forest Fire Centre
Edmonton, Alberta

(65) C.J. Ogilvie
Forestry Canada
Northwest Region
Northern Forestry Centre
Edmonton, Alberta
T6H 3S5

(66) Philip N. Omi
Professor
Colorado State University
Forest and Wood Sciences
Fort Collins, Colorado 80523
U.S.A.

(67) Donald F. Potts
School of Forestry
University of Montana
Missoula, MT 59812
U.S.A.

(68) Luc Pouliot
Superintentendent
Forêt-meteo Unit
Québec Weather Centre
100 Alexis-Nihon Blvd.
3rd Floor
Saint-Laurent, Québec
H4M 2N8

(69) Regis Proulx
Service de la Protection
Contre la Fer
Ministére de l'Energie et des
Ressources du Québec
1530 Blvd. de l'entente
Quebec City, Québec
G1S 4S7

(70) Elizabeth Reinhardt
Research Forester
USDA, Forest Service
Intermountain Research Station
P.O. Box 8089
Missoula, MT 59807
U.S.A.

(71) Paul G. Rivard
Department of Forest Science
University of Alberta
Edmonton, Alberta
T6G 2H1

(72) John O. Roads
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, CA 92093
U.S.A.

(73) Richard C. Rothermel
Project Leader
USDA, Forest Service
Intermountain Fire Sciences Laboratory
P.O. Box 8089
Missoula, MT 59807
U.S.A.

(74) Richard L. Rothwell
Department of Forest Science
University of Alberta
Edmonton, Alberta
T6G 2H1

(75) Kevin C. Ryan
Research Forester
Intermountain Fire Sciences Laboratory
P.O. Box 8089
Missoula, MT 59807
U.S.A.

(76) Lucy A. Salazar
Pacific Southwest Forest and Range
Experiment Station
USDA Forest Service
Riverside Fire Laboratory
4955 Canyon Crest Drive
Riverside, CA 92507
U.S.A.

(77) Rodney W. Sando
Administrator
State of Minnesota
Department of Natural Resources
Bureau of Real Estate Management
500 Lafayette Road
St. Paul, MN 55155.
U.S.A.

(78) Albert J. Simard
U.S. Forest Service
1407 South Harrison Rd.
East Lansing, MI 48823
U.S.A.

(79) Dennis G. Simmerman
Intermountain Science Laboratory
Intermountain Research Station
USDA Forest Service
P.O. Box 8089
Missoula, MT 59807
U.S.A.

(80) Brad J. Snyder
Alberta Weather Centre
Atmospheric Environment Service
Twin ATRIA Bldg.
4999-98th Avenue
Edmonton, Alta
T6B 2X3

(81) William T. Sommers
Forest Fire & Atmospheric Sciences Research
Forest Service, USDA
P.O. Box 96090
Washington, DC 20090-6090
U.S.A.

(82) B.M. Steele
Statistical Consultant
401 Plymouth
Missoula, MT 59801
U.S.A.

(83) George Stephens
NOAA, National Environmental Satellite,
Data, and Information Service
E/SP22, Mail Stop H
Washington, D.C. 20233
U.S.A.

(84) Brian J. Stocks
Forest Fire Research Officer and
Head, Forest Fire Research Unit
Forestry Canada
Great Lakes Forestry Centre
P.O. Box 490
Sault Ste. Marie, Ontario
P6A 5M7

(85) Roger Street
Environment Canada
4905 Dufferin Street
Downsview, Ontario
M3H 5T4

(86) J.P. Thorpe
Saskatchewan Research Council
15 Innovation Blvd.
Saskatoon, Saskatchewan
S7N 2X8

(87) Tia-houn Tsou
Department of Statistics
University of California
Riverside, CA 92521
U.S.A.

(88) Kyozo Ueyoshi
Scripps Institution of Oceanography
University of California, San Diego
La Jolla, CA 92093
U.S.A.

(89) Charles E. Van Wagner
Forestry Canada
Petawawa National Forestry Institute
P.O. Box 2000
Chalk River, Ontario
K0J 1J0

(90) R. Van Wyngaarden
Tydac Technologies Inc.
1600 Carling Ave., Suite 310
Ottawa, Ontario
K1Z 8R7

(91) Dale D. Wade
Research Forester
United States Department of Agriculture
Forest Service
Southwestern Forest Experiment Station
Route 1, Box 182A
Dry Branch, GA 31020
U.S.A.

(92) Darold E. Ward
Intermountain Science Laboratory
Intermountain Research Station
USDA Forest Service
P.O. Box 8089
Missoula, MT 59807
U.S.A.

(93) Paul C. Ward
Research & Development Section
Aviation and Fire Management Centre
OMNR, 747 Queen St. E.
P.O. Box 310
Sault Ste. Marie, Ontario
P6A 5L8

(94) Ross Wein
Department of Forest Science
University of Alberta
Edmonton, Alberta
T6G 2H1

(95) David R. Weise
Forester, RWU-PSU-4403
USDA, Forest Service
Pacific Southwest Forest & Range
Experiment Station
4955 Canyon Crest Dr.
Riverside, CA 92507
U.S.A.

(96) Elaine Wheaton
Saskatchewan Research Council
15 Innovation Blvd.
Saskatoon, Saskatchewan
S7N 2X8

(97) B.T. Whistler
Cooperative Institute for Climate Studies
Department of Meteorology
University of Maryland
College Park, MD 20742
U.S.A.

(98) Reinhold Winterer
Alberta Weather Centre
Atmospheric Environment Service
Twin ATRIA Bldg.
4999-98th Avenue
Edmonton, Alta
T6B 2X3

(99) Paul M. Woodard
Department of Forest Science
University of Alberta
Edmonton, Alberta
T6G 2H1

(100) Gene L. Woolridge
USDA Forest Service
Rocky Mountain Forest and
Range Experiment Station
240 West Prospect
Fort Collins, CO 80526-2098
U.S.A.

(101) G. Xanthopoulos
Graduate Student
Department of Forestry
University of Montana
Missoula, MT 59812
U.S.A.

(102) Yang Yun-Qian
Heilongjiang Forest Protection Ins.
Hapin Road No. 7, Harbin
People's Republic of China

Field Trip - Hybrid Poplar Technology/ Voyage de familiarisation - Technologie de peuplier hybride

Mr. Brian Barkley
Regional Forester
Ontario Ministry of Natural Resources
2002 Concession Road
Kemptville, Ontario
K0G 1J0

Mr. Ron Evers
Coordinator
Fast Growing Forest Group
Ontario Ministry of Natural Resources
Oxford Avenue
Brockville, Ontario
K6V 5V8

Commercial Exhibitors' Addresses/Addresses des exposants commercial

Agema
5230 South Service Road
Suite 125
Burlington, Ontario
L7L 5K2
416-637-5696

Canadian Helicopters Corp. (Sponsor)
Buttonville Airport
Markham, Ontario
L3P 3J9
416-940-1942

Campbell Scientific
9525 41st Avenue
Edmonton, Alberta
T6E 5X7
403-461-5158

Chemonics Industries Canada Ltd.
455 Dene Dr.
Kamloops, B.C.
V2H 1J1
604-374-0379

Forest Technology Systems
841 Goldstream Ave.
Victoria, B.C.
V9B 2X8
604-478-5561

Geneq
223 Signet Drive
Weston, Ontario
M9L 1V1
416-747-9889

Intera Technologies Ltd.
1525 Carling Ave., Suite 600
Ottawa, Ontario
K1Z 8R9
613-728-6111

Kavouras Inc.
FAA Bldg.
6301 34th Ave. S.
Minneapolis, Minn. 55450
612-726-9515

Lightning Location and Protection
4500 S. Lakeshore Dr., Suite 339
Tempe, AZ 85282
602-820-4175

MacLaren Plansearch
1959 Upper Water St., Suite 701
Halifax, N.S.
B3J 3N2
902-421-3200

Premo Plastics
863 Viewfield Rd.
Victoria, B.C.
V9A 4V2
604-382-3023

R. Scan
1200 Washington Ave. S.
Minnesota Supercomputer Centre
Suite 2170
Minneapolis, Minn. 55415-1258
612-333-1424

Tydac Technologies
1600 Carling Ave., Suite 310
Ottawa, Ontario
K1Z 8R7
613-722-7472

Wajax Manufacturing Ltd.
1100, rue Normal, Bureau 200
Lachine, Que.
H8S 1A6
514-637-5572

World Weatherwatch
7050 Woodbine Ave., Suite 100
Markham, Ontario
L3R 4G8
416-477-4120

(3)

(13)

(9)

(22)

(12)

(27)

(31)

(38)

(32)

(40)

(35)

(41)

(44)

(50)

(46)

(51)

(47)

(54)

(58)

(67)

(59)

(68)

(64)

(69)

(73)

(78)

(75)

(81)

(76)

(84)

(85)

(91)

(88)

(92)

(89)

(93)

(96)

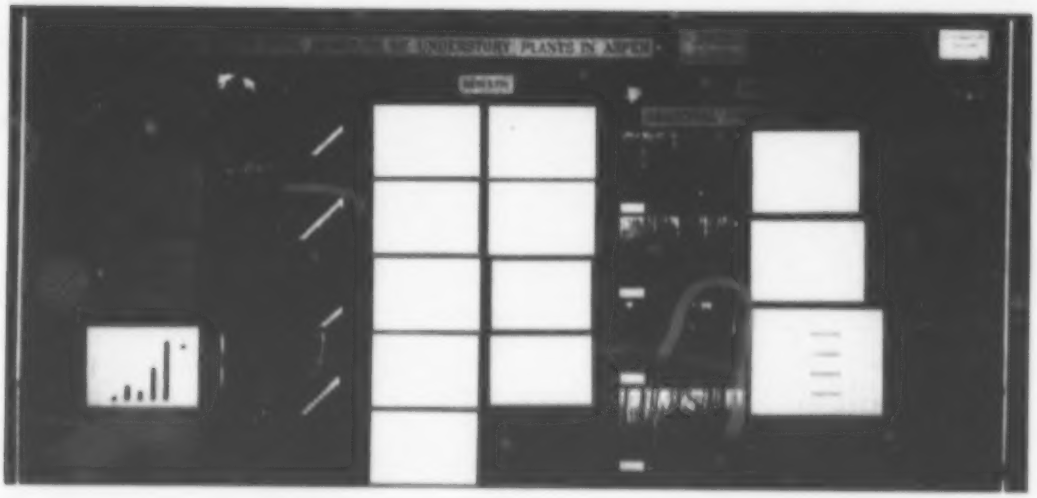
(102)

Note: Numbers in brackets refer to the authors identified on pages 447 to 453.

M.E. Alexander
R.W. Sando

FIRE BEHAVIOR AND EFFECTS IN ASPEN
- NORTHERN HARDWOOD STANDS

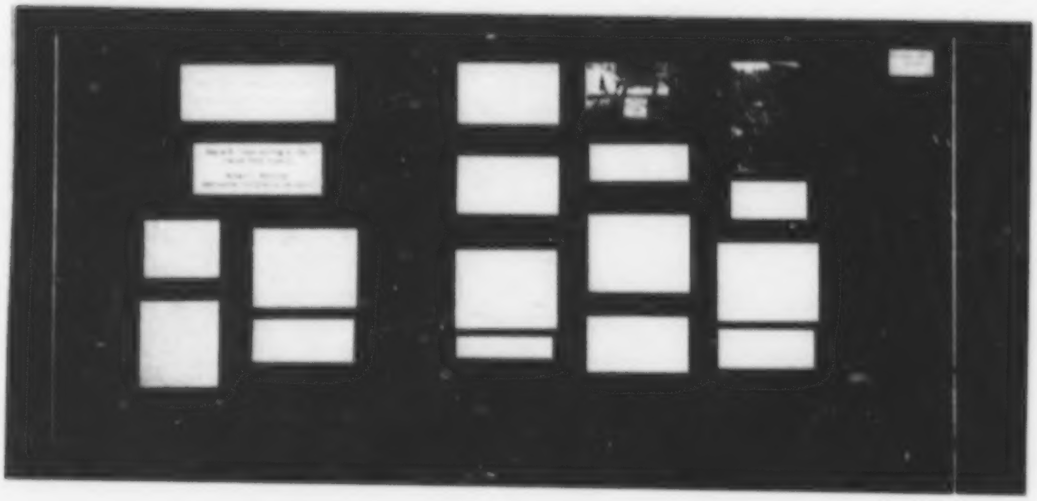
J.K. Brown
G.D. Booth
D.G. Simmerman


UNDERSTORY PLANTS IN ASPEN

R.E. Burgan

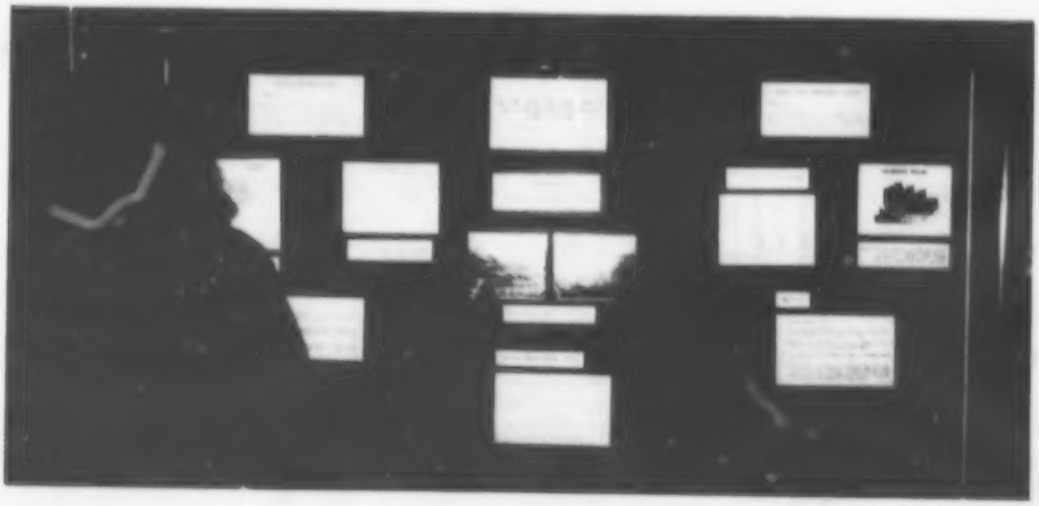
NATIONAL FIRE DANGER RATING SYSTEM

W.B. Cohen
P.N. Omi
R.C. Rothermel

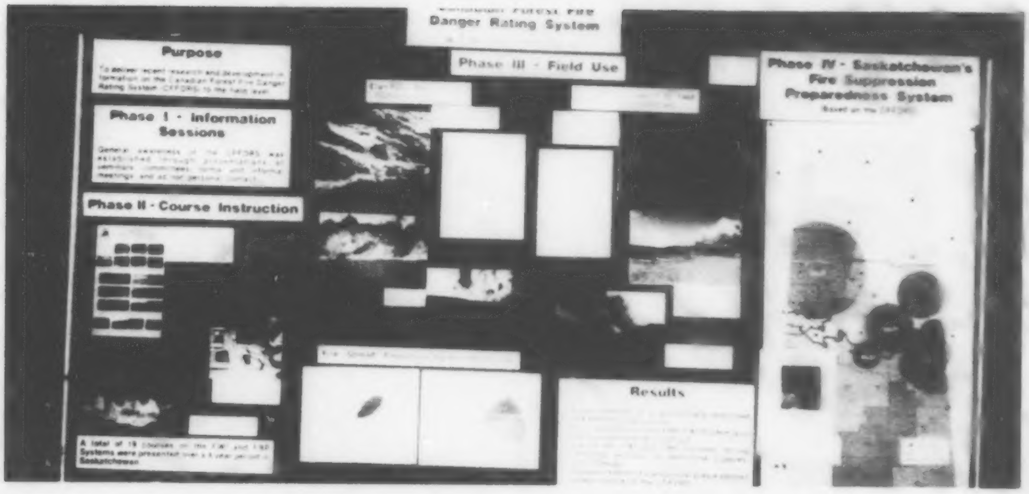


B.H. Connell
G.L. Woodridge
D.G. Fox

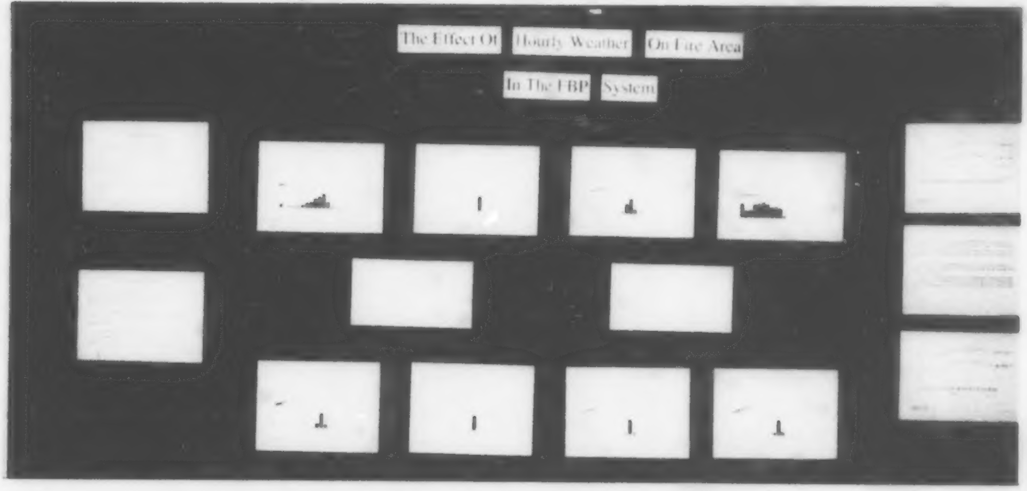
M.R. Coyea
V.J. Lieffers
P.M. Woodard



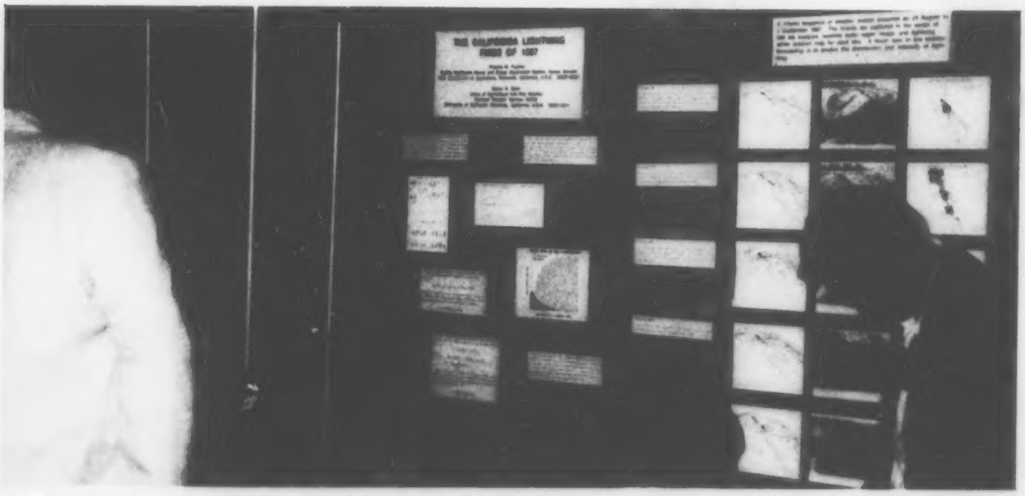
W.J. DeGroot


Danger Rating System
Purpose
Phase I - Information Sessions
Phase II - Course Instruction
Phase III - Field Use
Phase IV - Saskatchewan's Fire Suppression Preparedness System
Results

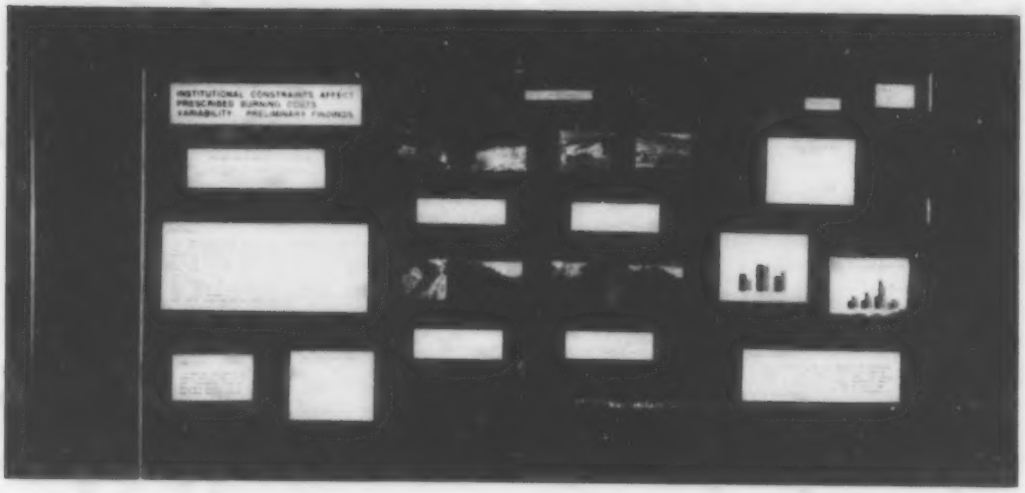
J. Feunekes
I.R. Methven


The Effect Of
Hourly Weather
On Fire Area
In The FBP
System

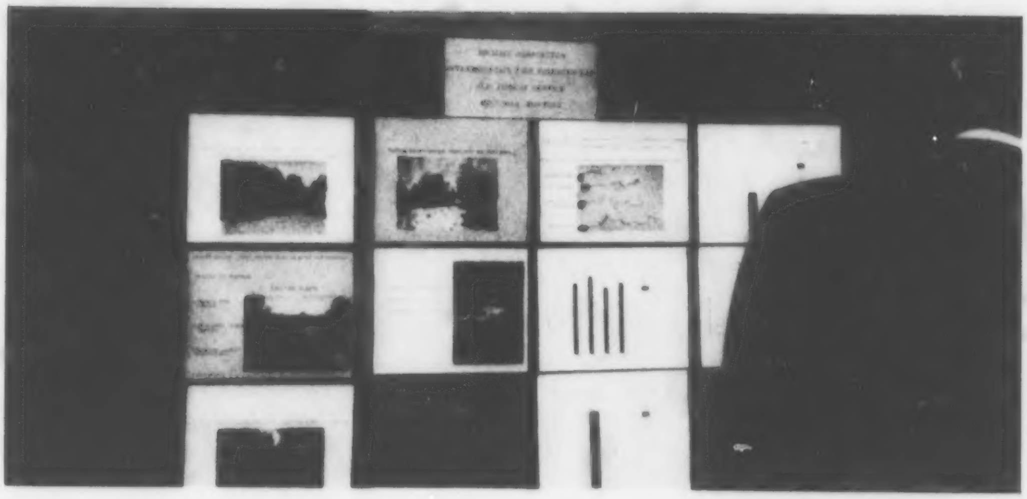
F.M. Fujioka
N.A. Dean


THE CALIFORNIA LIGHTNING FIRES OF 1987

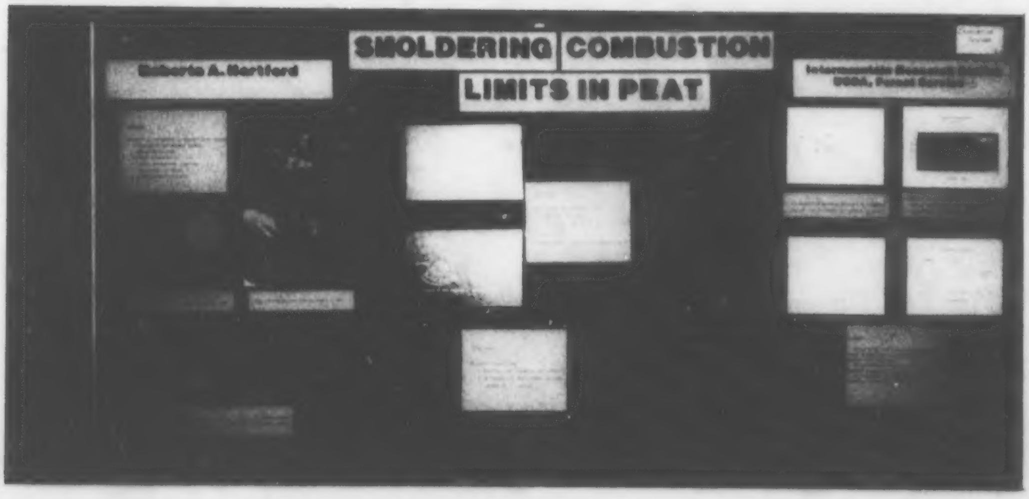
A. González-Cabán
L. Bednar


INSTITUTIONAL CONSTRAINTS AFFECT
PRESCRIBED BURNING COSTS
VARIABILITY: PRELIMINARY FINDINGS

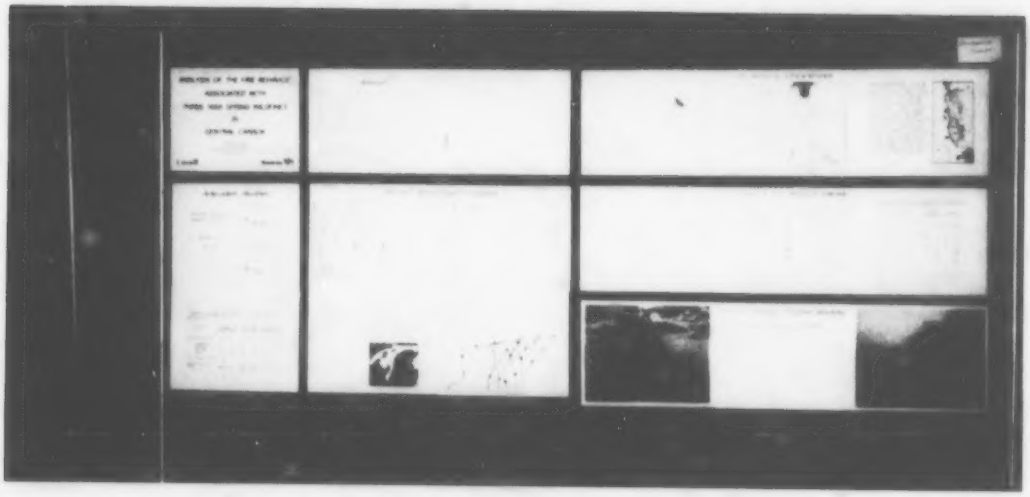
M.G. Harrington



R.A. Hartford

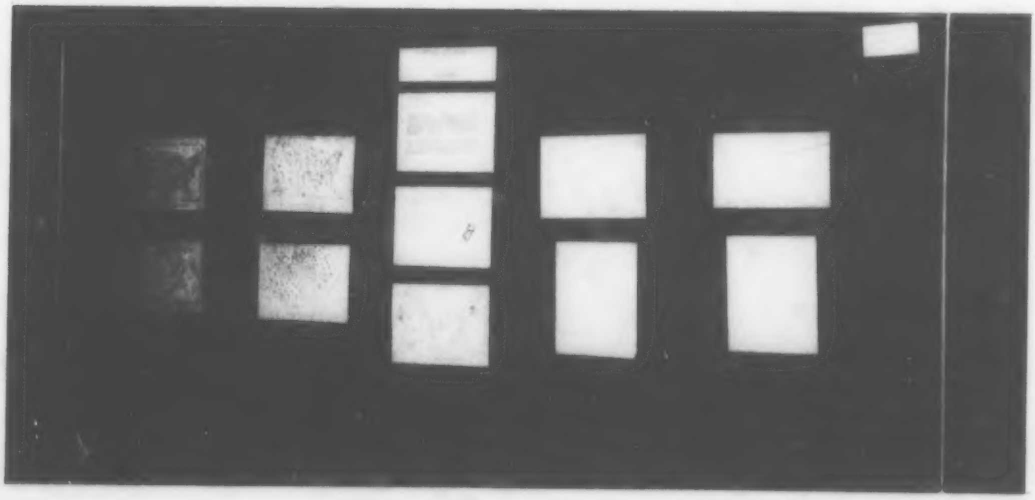

SMOLDERING COMBUSTION
LIMITS IN PEAT
Roberta A. Hartford
Intermountain Research Station
USDA, Forest Service

K.G. Hirsch



R.D. Hungerford

W.H. Klein

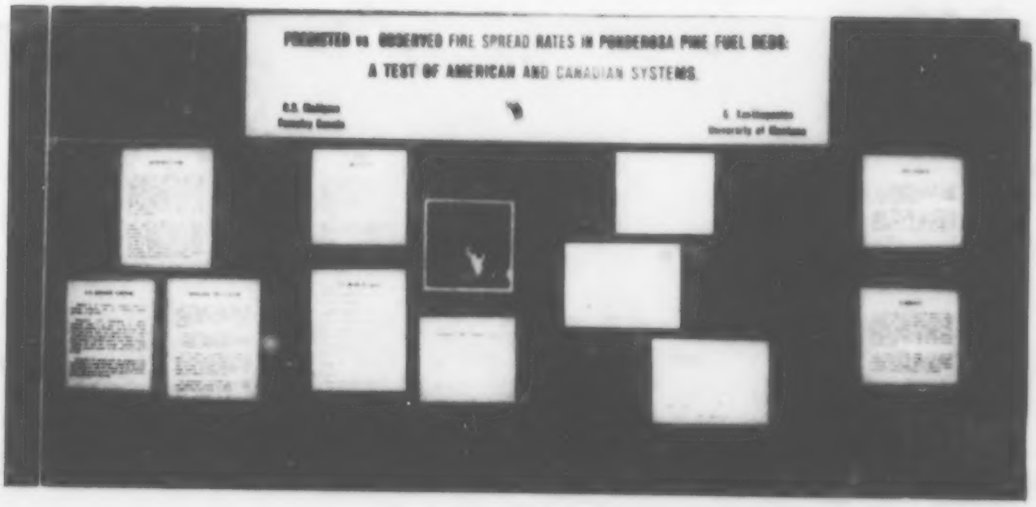


R.A. Lanoville
W.M. Mawdsley

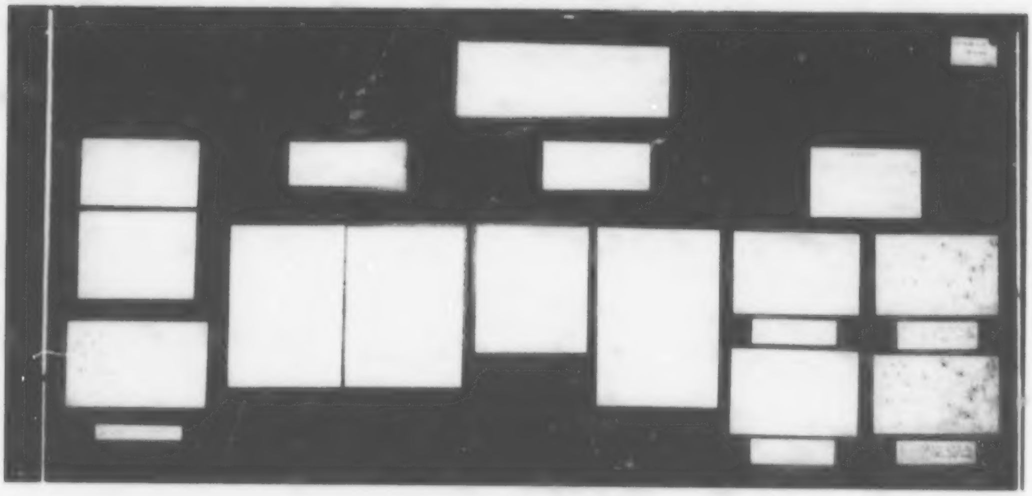
B.S. Lee
K.R. Anderson

Forestry Canada
Forêts Canada
A Spatial Analysis Approach for Forest Fire Preparedness Planning
Canada

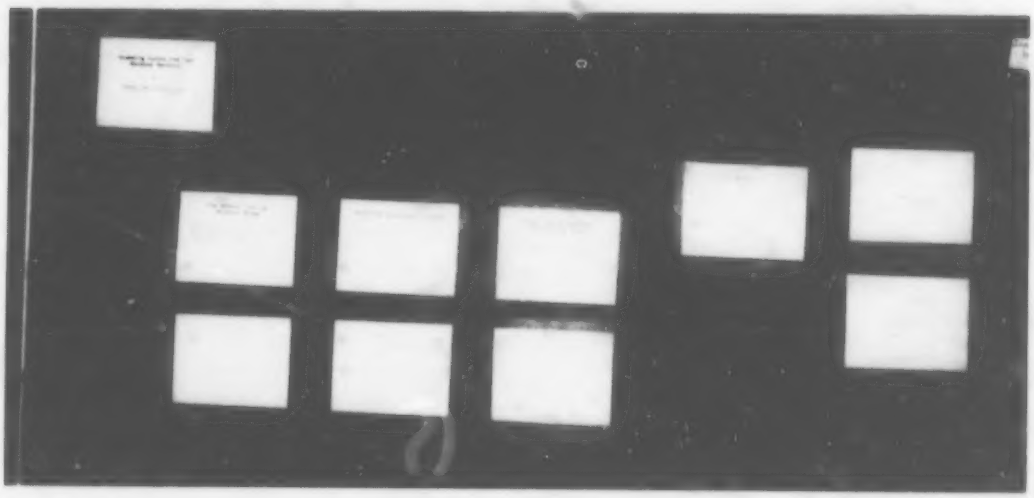
R.S. McAlpine
G. Xanthopoulos


PREDICTED vs OBSERVED FIRE SPREAD RATES IN PONDEROSA PINE FUEL BEDS:
A TEST OF AMERICAN AND CANADIAN SYSTEMS.

D.J. McRae
W.A. Main

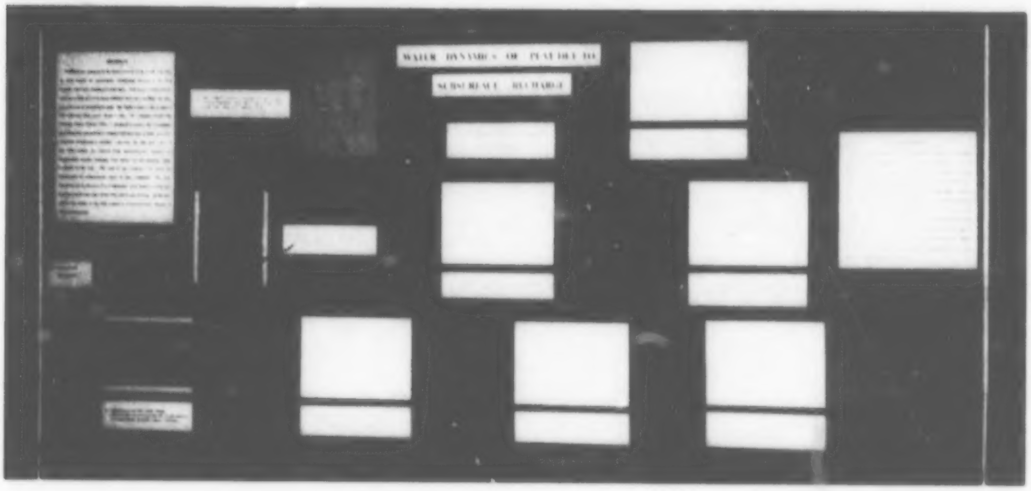


D.F. Potts
G.A. Morris

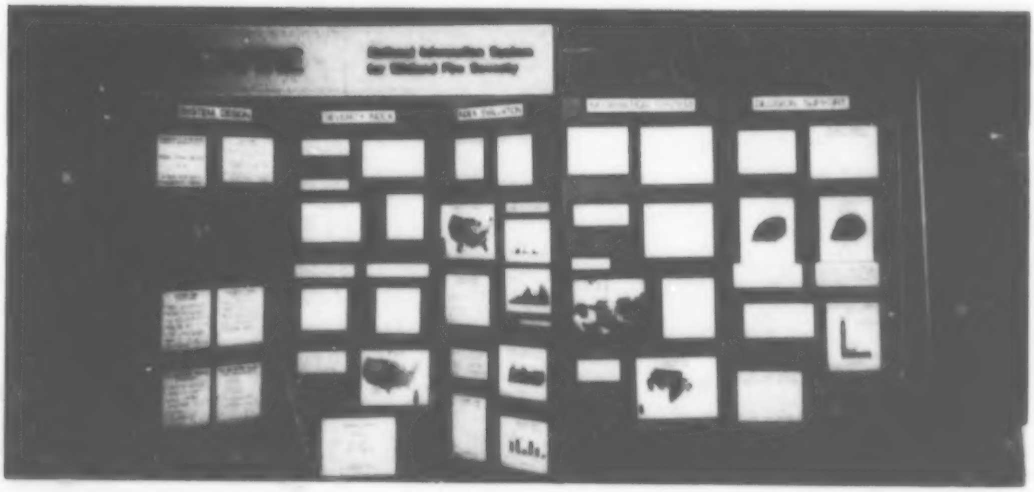


E. Reinhardt
J.K. Brown
W.C. Fisher

P.G. Rivard
R.L. Rothwell
P.M. Woodard


WATER DYNAMICS OF
SUBSURFACE RECHARGE

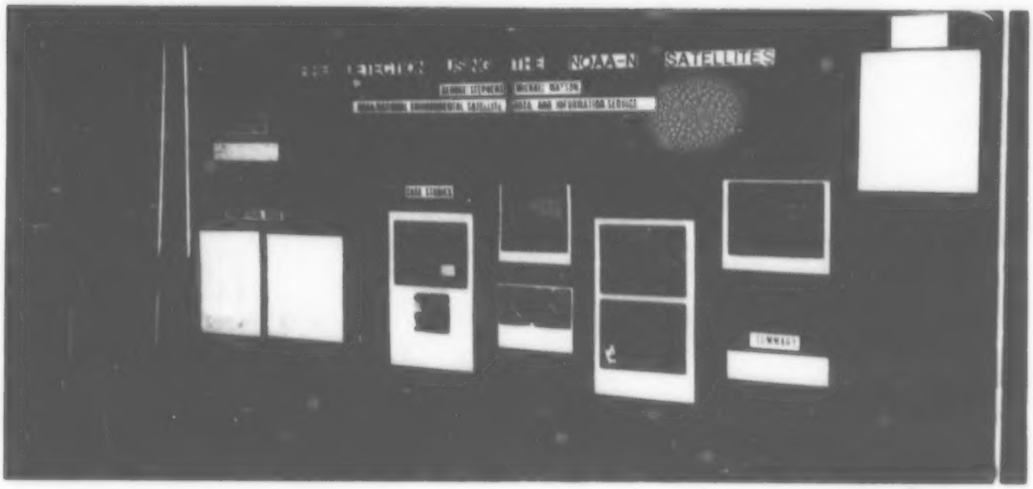
A.J. Simard
J.E. Eenigenburg
W.A. Main


National Information System
for Wildland Fire Severity
SYSTEM DESIGN
DECISION SUPPORT

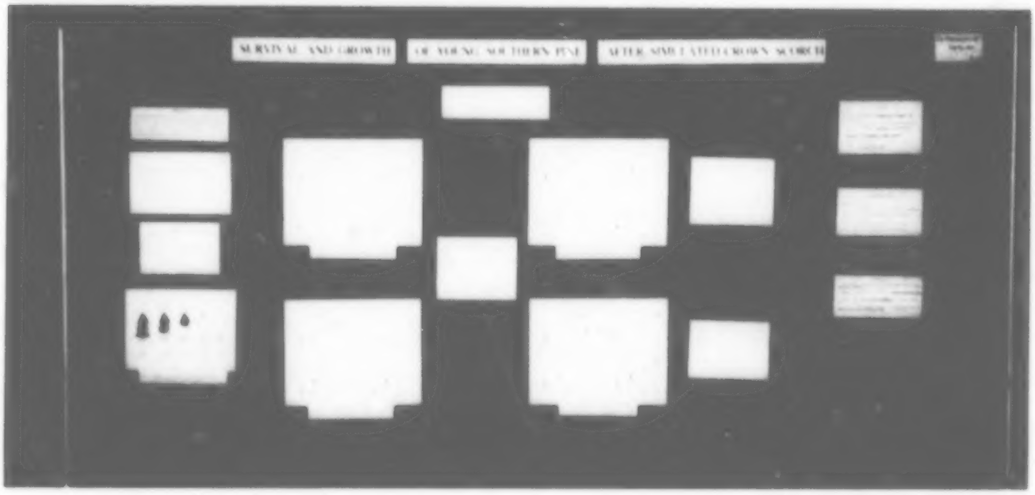
B.J. Snyder

A FIELD WORKSTATION FOR FIRE WEATHER
FORECAST SUPPORT
FEATURES

G. Stephens
M. Matson


FIRE DETECTION USING THE NOAA-N SATELLITES
CASE STUDIES
SUMMARY

D.R. Weise
D.D. Wade
R.W. Johansen


SURVIVAL AND GROWTH OF YOUNG SOUTHERN PINE AFTER SIMULATED CROWN SCORCH

Yang Yun-Qian

MONITOR OF THE [illegible] EXTREME FIRE IN DAXINGANLING AND
SURVEY OF [illegible] USING SPACE REMOTE SENSING IMAGES

Field Trip - Hybrid Poplar Technology/ Voyage de familiarisation - Technologie de peuplier hybride

Photographs/Photos

Sponsors

Environment Canada
Forestry Canada
Ministere de l'Energie et des Ressources du Québec
Ontario Ministry of Natural Resources

With the cooperation of...

American Meteorological Society
Canadian Institute of Forestry
Canadian Meteorological and Oceanographic Society
Society of American Foresters

Commanditaires

Environnement Canada
Forêts Canada
Le ministère de l'Energie et des Ressources du Québec
Le ministère des Ressources naturelles des l'Ontario

Collaborateurs

L'American Meteorological Society
L'Institut forestier du Canada
La Société météorologique et océanographique
La Society of American Foresters